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FATIGUE CRACK GROWTH OF GUN TUBE STEEL UNDER SPECTRUM LOADING

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Due to various internal pressures generated by different classes of ammunition, the service loads of a gun tube are variable in nature. Previous investigations into the service lives of gun tubes have shown that fatigue lives are often shorter than the bore wear lives; hence, accurate prediction of gun tubes' fatigue lives is important.

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20. ABSTRACT (CONT'D)

Several fatigue crack growth models for variable amplitude loading exist. This study compares three models, a no-load-interaction model, a Modified Wheeler model, and a Generalized Willenborg model, for four variable amplitude load histories. Predicted fatigue crack growth lives were compared with actual test lives and good correlation was achieved for all models. The Generalized Willenborg model yields the best overall load spectrum life prediction, but all three models predicted lives within a factor of 2.0 of the experimental lives.

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This work also constituted a thesis for the Master of Science Degree, which was completed by Captain Dennis while on educational assignment at Virginia Tech.

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LIST OF SYMBOLS

SYMBOL	EXPLANATION
a	Crack length
a_i	Instantaneous crack length
a_{oL}	Crack length at overload
a_o	Initial crack length
A	Material constant
B	Specimen thickness
C	Material constant - da/dN vs. ΔK coefficient
C_{pi}	Wheeler retardation parameter
da/dN	Crack growth rate
K	Stress intensity factor of fracture mechanics
m	Material constant for Walker equation
max,min	Subscripts indicating the maximum or minimum value of a cyclically varying quantity
n	Material constant - da/dN vs. ΔK slope
oL	Subscripts of superscript indicating the value corresponding to an overload cycle
P	Applied load
r_{yi}	Instantaneous plastic yield zone radius
r_{oL}	Plastic zone radius caused by overload
R	Ratio of minimum to maximum loads ($R = P_{min}/P_{max}$)
S	Overload shutoff ratio
t	Shaping parameter

SYMBOL	EXPLANATION
W	Specimen width
X	Load-to-crack distance for arc-shaped specimen
σ_y	Material yield strength
ΔK	Range of K for cyclic loading ($\Delta K = K_{max} - K_{min}$)
ΔK_{Th}	Range of K for R = 0 cyclic loading below which no crack growth occurs.

I. INTRODUCTION

The purpose of this research project is to investigate some specific analytical procedures to predict fatigue crack growth rates in A723 (similar to AISI 4340) steel under actual service conditions.

Due to the various internal pressures generated by different classes of ammunition, the service loads of a gun tube are variable in amplitude. Since firing patterns cannot be specified for the life of a tube, the service history is also random in nature. Currently, the useful life of a gun tube is determined by tube bore wear data and/or fatigue life data and is expressed in terms of Effective Full Charge (EFC) rounds. The class of ammunition generating the highest load on the tube is assigned an EFC rating of 1.0 and lesser classes of ammunition are assigned appropriate fractions.

Investigations into determining gun tube lives often find that fatigue lives are shorter than wear lives of the bores.(1) For this reason, accurate prediction of a gun tube fatigue life is important. Many fatigue crack growth analyses have been based on constant amplitude load conditions. This approach fails to account for the interaction effects of variable amplitude loads. It has been shown that periodic overloads retard crack growth while compressive loads can accelerate crack growth or reduce the retarding effects of a tensile overload(2).

There are many fatigue crack growth models in use today that attempt to account for the interaction effect of variable amplitude

loads. However, since no one model has been shown to work for all situations, no consensus exists as to the proper method to be used for predicting crack growth under variable amplitude loading.

This project will investigate three of the simpler fatigue life prediction models for variable amplitude loading for typical gun tube load spectra. Comparisons will be made with experimental data and recommendations on a fatigue life prediction method will be made.

II. LITERATURE REVIEW

The study of fatigue crack growth under variable amplitude loading has progressed rapidly over the past 20 to 25 years. Numerous studies of fatigue crack growth have been done for constant amplitude loading. However, as refined as the resulting life prediction methods became, they were of limited use in the many areas of fatigue where the actual service load histories were of a variable, irregular or random nature with respect to time or stress amplitude. The railroad, automotive, and, in particular, the aerospace industries were the primary developers of more efficient methods to predict service life under variable amplitude loading.

A myriad of factors affecting fatigue crack growth under service loading have been investigated. The most important external factors are the moisture, temperature and atmospheric conditions that a structure is subjected to during its life(3). Very significant changes in crack propagation occur when these elements are varied. Thus, corrosion fatigue is a large and important area of current research.

Other factors also affect fatigue crack growth rates. Musuva and Radon (1979)(4) have found that the stress range and frequency of cycles have definite, but not cumulative, effects. Loading mode and crack size have also been found to greatly influence the rate of crack growth in materials. Since short cracks were found to behave in a vastly different manner than long cracks,(5,6,7) the study of

short crack growth has become another important area of current research.

Early attempts at accounting for variable load effects ignored sequence effects. Palmgren(8) and Miner(9) (1945) used the concept of cumulative damage to predict fatigue life for variable loads. They defined the damage, D, done by one block of cycles with n cycles per block as:

$$nD = \frac{n}{N}$$

where N is the mean number of cycles to failure and n is the number of repeated cycles in a block at a stress level. When:

$$\sum_{i=1}^{m} \frac{n_i}{N} = 1$$

failure is predicted.

Though results obtained from this early model sometimes provided reasonable correlation with experimental results, a number of cases of inaccuracy were found, and it became clear that improvement was needed.

Once the importance of load interaction and sequence effects of variable amplitude cyclic stresses was recognized, extensive studies began on developing methods of accounting for their effects on fatigue crack growth rates. Investigation into load sequence effects found that occasional tensile overloads retarded the rate of crack growth in a specimen subjected to subsequent load cycles of smaller amplitude(10,11). If the overload was high enough, crack arrest

could occur. It was initially thought that compressive loads did not contribute to crack growth. Later research found that a compressive overload following a tensile overload could reduce the level of retardation and that an initial compressive overload could, in fact, accelerate crack growth.(12) (13)

The first generation of models to account for sequence effects used a fracture mechanics approach to explain sequence effects. The most widely accepted explanations are those that consider crack closure and residual stress effects.

Elber(14) (1971) found that a crack subjected to zero to maximum tensile loading did not open until part way through a loading cycle, and that it closed before the remotely applied stress became zero. Thus, the effective stress range to grow a crack was the maximum remotely applied stress minus the crack opening stress. Retardation of crack growth due to a tensile overload was attributed to a higher crack opening stress due to the plastic zone created by the overload. Further refinements of the crack closure model have now made the crack closure the most complete model for prediction of fatigue crack growth. These models, however, are very expensive to use unless some potentially dangerous simplifying assumptions are made.

The residual stress hypothesis used in the models of Wheeler, Willenborg, Gallagher, and others says that the tensile overstrain causes a residual compressive stress field in the area of the crack

tip. This residual stress field attempts to halt crack growth until the local stress at the crack tip caused by the remotely applied load exceeds the residual compressive stress.

Wheeler[15] (1972) introduced a fatigue crack growth model that was a "first-order improvement" on the Miner equation by considering the effect of the residual stress field following a tensile overload by introducing a retardation parameter into the Paris crack growth equation. The Paris equation hypothesized that there was a linear relationship between the logarithm of the crack growth rate and the logarithm of the stress intensity factor range:[16]

$$\frac{da}{dN} = f(\Delta K) = A(\Delta K)^n \qquad (1)$$

Modifications of the Paris equation to include mean stress effects were made by Walker[17] and Forman[18]. Wheeler's retardation parameter, C_{pi}, was defined as:

$$C_{pi} = \left[\frac{r_{yi}}{a_{oL} + r_{oL} - a_i}\right]^t \quad ; \quad (a_i + r_{yi}) < (a_{oL} + r_{oL}) \qquad (2)$$

$$C_{pi} = 1 \quad ; \quad (a_i + r_{yi}) > a_{oL} + r_{oL} \qquad (3)$$

where:

r_{yi} = instanta-eous plastic zone length

a_{oL} = crack length at time of overload

r_{oL} = plastic zone length caused by overload

a_i = instantaneous crack length

t = shaping exponent

Wheeler applied this retardation to the crack growth rate after an overload such that the crack length after n cycles, a_n, is:

$$a_n = a_o + \sum_{i=1}^{n} C_{pi} \left[\frac{da}{dn}\right]_i \tag{4}$$

where a_o is the initial crack length. Wheeler originally thought the t-exponent was constant for each material. Gray and Gallagher[19] (1976) later found this not to be true. Wheeler's model implies that crack growth rate retardation will occur as long as the instantaneous plastic zone is within the overload plastic zone. His model is useful on histories similar to those used to obtain t and where compression load effects are not significant.

Willenborg[20] considered an effective stress concept to reduce the stress intensity factor at the crack tip. Willenborg's model assumed that some crack-tip compressive self-stress was present after an overload. He used this residual stress value to calculate an effective stress intensity factor. Utilizing constant amplitude crack growth data, Willenborg computed the crack growth by considering the retardation effect to decay over the length of the overload plastic zone. This model also does not apply to compressive loads. Willenborg's model can be expressed as:

$$a_p = a_i + C\left(\frac{K_{req}}{\sigma_y}\right)^2 \tag{5}$$

where C is a geometric parameter, σ_y is the yield strength of the

material, and K_{req} is a measure of the stress required to produce a yield zone large enough to end retardation. Using this approach an effective load ratio, R_{eff}, can be computed along with an effective stress intensity factor range, ΔK_{eff}, that may be used in a Paris (or similar) crack growth rate equation.

Improvements on the Willenborg model have been made by Gallagher(21) (1974) and Chang(22) (1978) that allow for stress intensity factor threshold effects and compressive loads, respectively. These improvements yield good results in many cases.

For load histories of a more statistically random nature, Hudson(23) and others have had success using a root-mean-square stress intensity factor range. For cases where non-random loading occurs with few high load cycles which cause long delays in crack growth, significant error usually results.

A sophisticated and current, non-fracture mechanics approach to fatigue life prediction under variable amplitude loading is based on plastic plane stress mechanics. This is the local strain approach, which is used primarily in studies of the crack initiation phase. This method assumes that the fatigue life of a specimen is primarily controlled by the notch surface strain(24). A model of the stress-strain behavior of the material is used to simulate the deformation history at the notch root. The local strain method has proven itself capable of handling the effects of local notch plasticity and also mean stress effects. It can be used effectively and accurately with

varying load histories, including large plastic strains. Some of the features of this approach, however, are applicable to crack growth. Saxena and Hudak [25] have made an attempt to expand this approach to analysis of the crack propagation stage.

III. ANALYSIS

The problem of fatigue crack growth in a gun tube can be effectively analyzed using the theory of linear elastic fracture mechanics (LEFM), which relates the stresses in the vicinity of a crack tip to a stress field parameter, or stress intensity factor, K. The value of K depends on the magnitude and mode of the loading, body geometry and crack length. An important restriction of LEFM is that the size of the plastic zone located at the crack tip be small relative to the geometry of the specimen. The radius of the plastic zone for a specimen in a state of plane stress is, according to Irwin's plastic zone model[28]:

$$r_{yi} = \frac{1}{2\pi} \left(\frac{K}{\sigma_y}\right)^2 \tag{6}$$

Using the previously mentioned Paris equation, equation number (1), predictions of crack growth rates can be made without consideration of mean stress effects. The Walker equation is a modified form of the Paris equation that does consider these mean stress effects. The Walker equation is expressed as:

$$\frac{da}{dN} = C\left[\frac{\Delta K}{(1-R)^{1-m}}\right]^n \tag{7}$$

where R is the ratio of the minimum to the maximum remotely applied loads, and C, m, n are material constants.

Determination of the material constants in the Walker equation is accomplished by reducing constant amplitude test results of crack

length versus cycles to determine stress intensity factor range (ΔK) and crack growth rate (da/dN). The data reduction routine used was an incremental polynomial method as described in ASTM Standard E647[27]. A computer program by Fong and Dowling[29] was modified to reduce data for the arc-shaped specimen (DATRED2) and is shown as an appendix.

After the constant amplitude test data is reduced, a standard least squares fit is applied to the data by using the Walker equation to define an equivalent stress intensity factor range as:

$$\Delta K_{eq} = \frac{\Delta K}{(1-R)^{1-m}} \qquad (8)$$

By varying the constant m, a best fit is determined. In particular, all data from various R-ratios should fall on one straight line on a log-log plot of da/dN vs. ΔK_{eq} (see Figure 9). Since none of the models used here incorporated the effects of compressive loads, the effective stress intensity factor range for a compressive load was set equal to K_{max} by setting m equal to zero. The data fitting computer program (DATFIT) is shown as an appendix.

Analytical predictions of service life under variable amplitude loading were made from three different models, a Modified Wheeler model,[19] a no-interaction model, and a Generalized Willenborg model[21].

The basic Wheeler model, as previously discussed, incorporates an empirical shaping factor, t, to fit the test data to the predicted

curve. Wheeler hypothesized that this shaping factor was a material constant, but was independent of other variables, such as load spectrum details and load level. Gray and Gallagher experimentally proved that the shaping factor was not only material dependent but was also dependent on ΔK and could be expressed as:

$$t = \frac{n}{2} \times \left\{\frac{\log\left[\frac{\Delta K}{\Delta K_{th}}\right]}{\log S}\right\} \tag{9}$$

where n is the exponent in the crack growth equation, ΔK_{th} is a lower threshold value (at R equal to zero) of stress intensity range below which crack growth does not occur, and S is an overload shutoff ratio such that crack arrest will occur for overloads that satisfy the following:

$$\frac{K_{max}^{oL}}{K_{max}} > S \tag{10}$$

The values of S = 2.3 and ΔK_{th} = 6 for AISI 4340 steel[19] were used since this is essentially the same material as A723 steel. For the no-interaction case, it is only necessary to set the shaping exponent, t, to zero. Thus, the Wheeler retardation parameter in equation (2) becomes 1.0 and the crack growth equation is not modified to account for retardation effects.

The Generalized Willenborg model uses an effective stress intensity factor that effectively reduces the actual stress intensity factor by an amount that is related to the overload induced plastic zone. The amount that the stress intensity factor is reduced is also

related to the overload shutoff ratio, S, and the threshold stress intensity factor range at R equal to zero, ΔK_{th}. The effective stress intensity factors are expressed as:

$$(K_{max})_{eff} = K_{max} - \Phi[K_{max}^{oL}(1 - \frac{\Delta a}{r_{oL}})^{1/2} - K_{max}] \qquad (11)$$

$$(K_{min})_{eff} = K_{min} - \Phi[K_{max}^{oL}(1 - \frac{\Delta a}{r_{oL}})^{1/2} - K_{max}] \qquad (12)$$

where:

$$\Phi = \frac{1 - \frac{(\Delta K_{th})/(1-R)}{K_{max}}}{S - 1} \qquad (13)$$

The overload plastic zone, r_{oL}, is computed using Irwin's plastic zone model, equation (6), with K_{max}^{oL}, and Δa is the crack growth since the overload.

Using these effective stress intensity factors, an effective load ratio can be expressed as:

$$R_{eff} = \frac{(K_{min})_{eff}}{(K_{max})_{eff}} \qquad (14)$$

and the Walker equation becomes:

$$\frac{da}{dN} = C[\frac{\Delta K}{(1 - R_{eff})^{1-m}}]^n \qquad (15)$$

It should be noted that:

$$\Delta K = K_{max} - K_{min} = (K_{max})_{eff} - (K_{min})_{eff} \qquad (16)$$

The crack growth prediction models are incorporated into a unified FORTRAN computer program (CRACK) that is listed in the appendix. This program is a cycle-by-cycle integration of crack growth based on the current crack length. In its present form, the program handles only the arc-shaped specimen, but it could be easily modified to accept any fatigue crack growth specimen geometry. Failure can be predicted based on brittle fracture or on total plastic yielding. For A723 steel, a value of fracture toughness (K_{Ic}) equal to 116.3 ksi $(\mathrm{in.})^{1/2}$ was furnished by Benet Weapons Laboratory. Calculations of failure based on total plastic yielding are accomplished using the method proposed by Dowling.[30] A critical crack length for total plastic yielding is computed by:

$$a_{crit} = (W + X)\ \{Q + 1 - [Q(Q + 4)]^{1/2}\} - X \qquad (17)$$

where:

$$Q = \frac{P}{1.26\ \sigma_y\ B(W + X)}$$

The maximum load in the history (P_{max}) was used to compute the critical crack length.

IV. EXPERIMENTAL INVESTIGATION

A. Test Material and Specimens

The material used in the tests was A723 steel with a 0.2% offset yield stress of 182.05 ksi. The specimens were machined from a section of an M68, 105 mm, 100% autofrettaged gun tube (serial #27272) selected by the U. S. Army Benet Weapons Laboratory. The rifling in the bore of the tube was removed and the outside diameter machined to a uniform value. Ten slices perpendicular to the longitudinal axis were made (see figure 1). The inner and outer tube diameters were measured for each slice. A radial cut was then made and the inner and outer tube diameters were again measured. The dimensions are shown in Table 1. Note that this radial cut relieves the autofrettage stress at all points through the cross-section, so that residual stresses in the test specimens are not a problem[26].

Each slice of gun tube was machined to a thickness of 0.25 inches. A total of 26 arc-shaped fatigue crack growth specimens and four "dogbone" tensile specimens were machined according to figure numbers 2 and 3. The tensile specimens were chosen from different locations along the length of the tube to account for any material inhomogeneity. Fatigue crack growth specimens were machined so that centerlines connecting the pin holes were tangent to the inner radius at the point of the notch root, thus, the load-to-crack distance (X) was zero. The crack starter notch was machined to 0.500 inches to

facilitate crack initiation. The test specimens were pre-cracked using a load shedding technique to further facilitate uniform crack growth. All specimen dimensions are in accordance with ASTM Standard E399.A5 on fracture toughness testing,[27] with the exception of the thickness, which was decreased to conform to the requirements of ASTM Standard E647[27] on fatigue crack growth.

B. Test Equipment

All fatigue and tensile tests were conducted using a closed-loop, electro-hydraulic axial testing machine (± 20,000 lb. static and dynamic range) manufactured by MTS Corporation. Constant load amplitude test signals were generated by the system function generator, while variable load amplitude test signals were generated by an IBM personal computer equipped with a Data Translation DT2805 digital-to-analog and analog-to-digital data acquisition board. Load histories were generated at 1000 conversions per second.

Crack growth was measured optically using a traveling microscope. The specimen surface was polished and reference scribe lines were placed at 0.1 inch intervals from the notch tip to facilitate measurement of the crack tip (see Figures 4 and 5). Load ranges were measured by an MTS digital peak recorder and verified using a Tektronix Model 7603 oscilloscope. Cycles for the variable load amplitude tests were computed by dividing the time as recorded on the timer on the MTS testing machine by the previously determined constant number of seconds for each repetition of the history.

C. Test Methods

A total of 12 constant amplitude and 12 variable amplitude tests were conducted. The constant amplitude tests were conducted at various load ratios to obtain material property data for analytical prediction models. (See Table 2 for description of tests.) Four variable amplitude load histories were chosen based on consultation with U. S. Army Benet Weapons Laboratory. The relative pressure levels of the top four zones of ammunition for the M68 105 mm tube were analyzed and four relative load levels of 1.0, 0.6, 0.45, and 0.33 were chosen. Two combinations of load cycles were chosen, and each of these histories was used in forward and reversed modes and three tests were run on each version of a history. Descriptions of the variable amplitude histories are included in Table 3. Figures 6 and 7 graphically depict the histories. The number of cycles at each level is not based on any established firing pattern since no standard firing sequence appears to exist. Hence, the histories were chosen to represent reasonable firing patterns. Actual test load levels are chosen to give a wide range of crack growth data. All minimum load levels in each history are identical and only the maximum load levels are varied. Load levels used in each test are detailed in Table 4.

Four tensile tests were performed to obtain material property data. Each specimen was loaded using the time controlled ramp load function of the MTS function generator to obtain a constant rate of

deflection. An MTS one-inch strain gage was used to measure strain. Both stroke and strain were plotted against load on an HP 7046B three channel X-Y chart recorder.

D. Results

Material data from tensile specimen tests is shown in Table 5. Constant amplitude test results and reduced data are included in Tables 6 through 17. Crack growth rate versus stress intensity factor range, ΔK, for the constant amplitude tests is shown in figure 8. Figure 9 shows the same data plotted against an equivalent range, ΔK_{eq}, which is discussed in detail below. Variable amplitude test results are summarized and compared with analytical predictions in Table 18 while Tables 19 through 30 give the detailed data. Graphical comparisons of test and analytical life predictions are displayed in summary form in figures 10 and 11. Detailed comparisons for each test are given in figures 12 through 23. The material constants determined from constant amplitude tests are:

$C = 2.73 \times 10^{-11}$	(growth rate constant in Walker equation)
$n = 3.24$	(slope of log-log crack growth rate curve in Walker equation)
$m = 0.42$	(empirical constant in Walker equation; $m = 0$ for loads which range into compression)

V. DISCUSSION

As shown in figure 10 and figures 11a, b, c, all three methods produce a predicted crack growth life that is within a factor of 2.0 of the experimental life. As expected, the no-interaction model generally yields slightly more conservative results since no retardation effects of tensile overloads are considered. Both the Modified Wheeler and the Generalized Willenborg models also yield statistically acceptable results for the test, though the Generalized Willenborg model yields more consistent predicted-to-actual life ratios. All three models yield slightly conservative predictions for the high load ratio (R = 0.7) tests. For the compressive load tests, the no-interaction model yields the most acceptable results, while the other two models predict slightly unconservative lives. It appears that neglecting both the retardation effects of overloads and the acceleration effects of compressive loads in the no-interaction model yields fairly good life predictions in tests with negative load ratios. The Modified Wheeler and Generalized Willenborg models yield slightly but consistently unconservative life estimates for the negative load ratio tests. This is probably due to the compressive cycles and their accelerating effects on crack growth being totally ignored.

Considering the entire spectrum of variable amplitude tests, a mean value of predicted-to-actual life ratio was computed for each model (refer to Table 18). The Generalized Willenborg model has a

mean predicted-to-actual life ratio of 1.098 with a standard deviation of 0.189. The Modified Wheeler model was slightly more unconservative, and the no-interaction model was slightly conservative, in their predictions.

All three models do yield acceptable predictions by current standards and appear to be valid approaches to predicting life under variable amplitude loading of the type studied for A723 steel. By ignoring the effects of compressive loads, the Modified Wheeler and Generalized Willenborg models as employed here do not consider effects that could in some cases be important to the life an an autofrettaged gun tube. The Willenborg/Chang model does have a method of accounting for the acceleration effects of compressive loads, and further work on life predictions using that version would be useful. The apparent trend of conservative predictions at high load ratios is also an area that could be further investigated.

In future tests it should be noted that the arc-shaped specimen is not an optimum specimen geometry for tests using tension-compression load cycles. Some of the compressive load histories used in this project experienced load spikes higher than programmed due to a slight gap between the pin and the specimen. Though both the pin and the specimen were correctly machined to within a specified tolerance, a small gap still existed that caused this anomaly. Alternate specimen geometries designed for compressive loads should be used, perhaps center cracked panels rigidly gripped.

Note that the conclusions reached may need to be modified for firing sequences which differ by a large amount from those employed in this study. For example, highly random patterns, or those with relatively more cycles at the lower levels, could result in different trends in comparisons between the various life predictions and experiment. In the comparisons shown by Chang[2] for highly irregular aircraft load spectra, the interaction effects were of similar magnitudes to those observed here, that is, no more than a factor of two in life. This, and the results of the present study, suggest that irregular load histories for gun tubes could be analyzed with reasonable confidence using the methods presented here. However, where there are relatively more cycles at the higher load levels than for the patterns used here, these cycles will dominate the behavior, making load interaction effects unimportant, so that the choice of a life prediction model is not critical.

Further work could conceivably be undertaken on the difficult task of obtaining typical field data on firing sequences and using these to develop standard load spectra. Such spectra could then be used with the life prediction models presented here, with some confirming test data being desirable also.

Note that gun tube usage involves elevated temperatures, and for cracks from the bore, hostile chemical environments. Some caution is needed in directly applying the results of this study, as both of these factors will tend to increase growth rates. Additional

laboratory study could be undertaken in these areas. An alternative would be to monitor some cases of crack growth in actual firing of gun tubes under known loading. Ths would provide a realistic basis for judging the effects on gun tube life due to these and other uncertainities in analytical life predictions. Hence, factors of safety could then be established that include these uncertainties.

VI. SUMMARY AND CONCLUSIONS

An investigation of three fatigue crack growth prediction models for variable amplitude loading was conducted and the resultant predicted lives were compared with experimental results. The Generalized Willenborg model yields the best overall load spectrum life predictions, though the no-interaction and Modified Wheeler models also yield life predictions that are within a factor of 2.0 of experimental lives. Further investigation into the effects of compressive loads and high load ratios could be done if greater accuracy is desired.

The theory of linear elastic fracture mechanics and basic crack growth models has been shown here to yield acceptable and relatively inexpensive fatigue crack growth life predictions for the case of variable amplitude loading of gun tubes. More expensive and complex predictive models could be tried but may not yield statistically more accurate results.

Additional information on typical firing sequences in the field would be desirable in any future work in this area. Also, the monitoring of crack growth during some cases of actual firing of gun tubes may be desirable.

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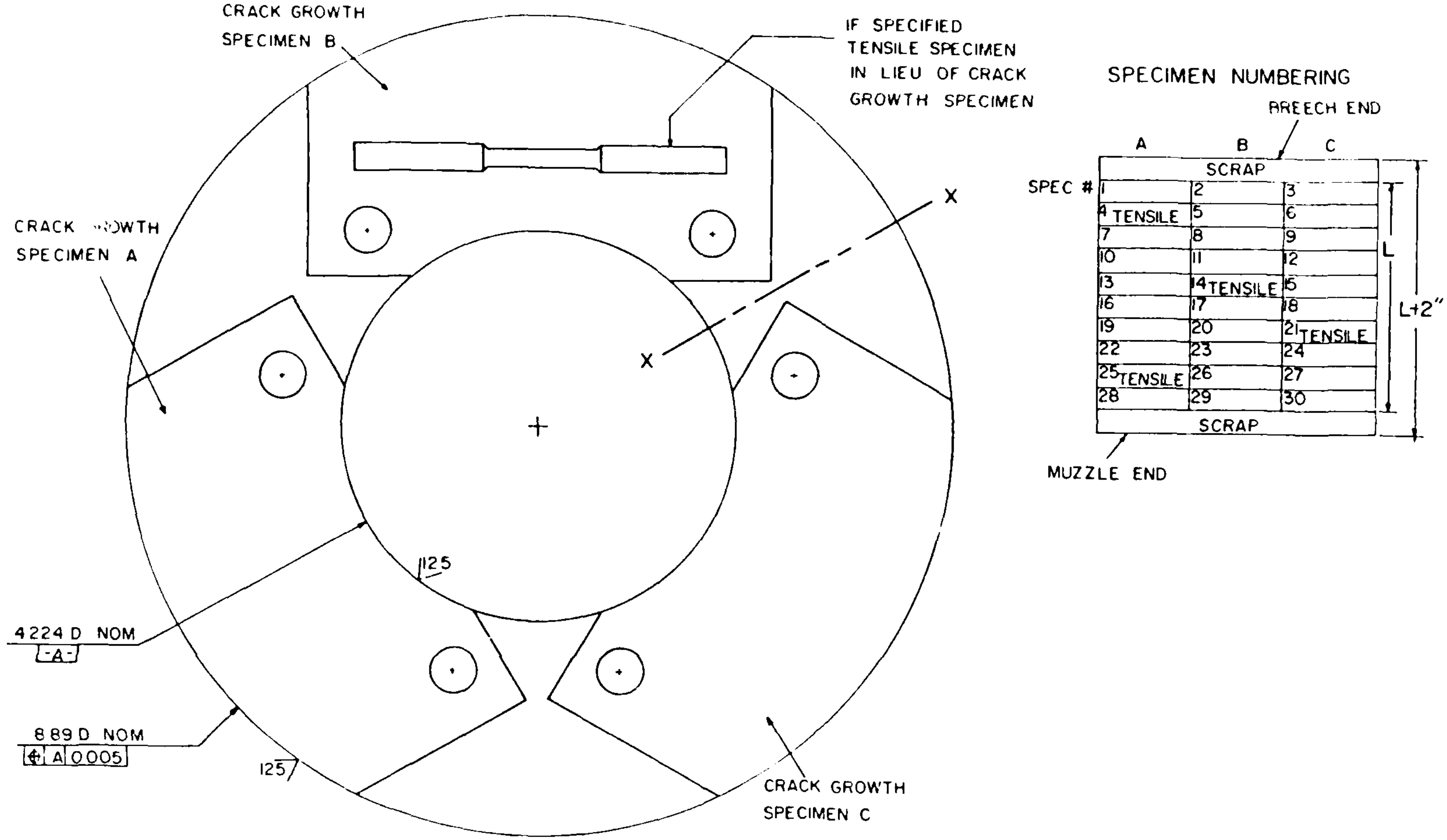

Figure 1: Gun tube specimen details.

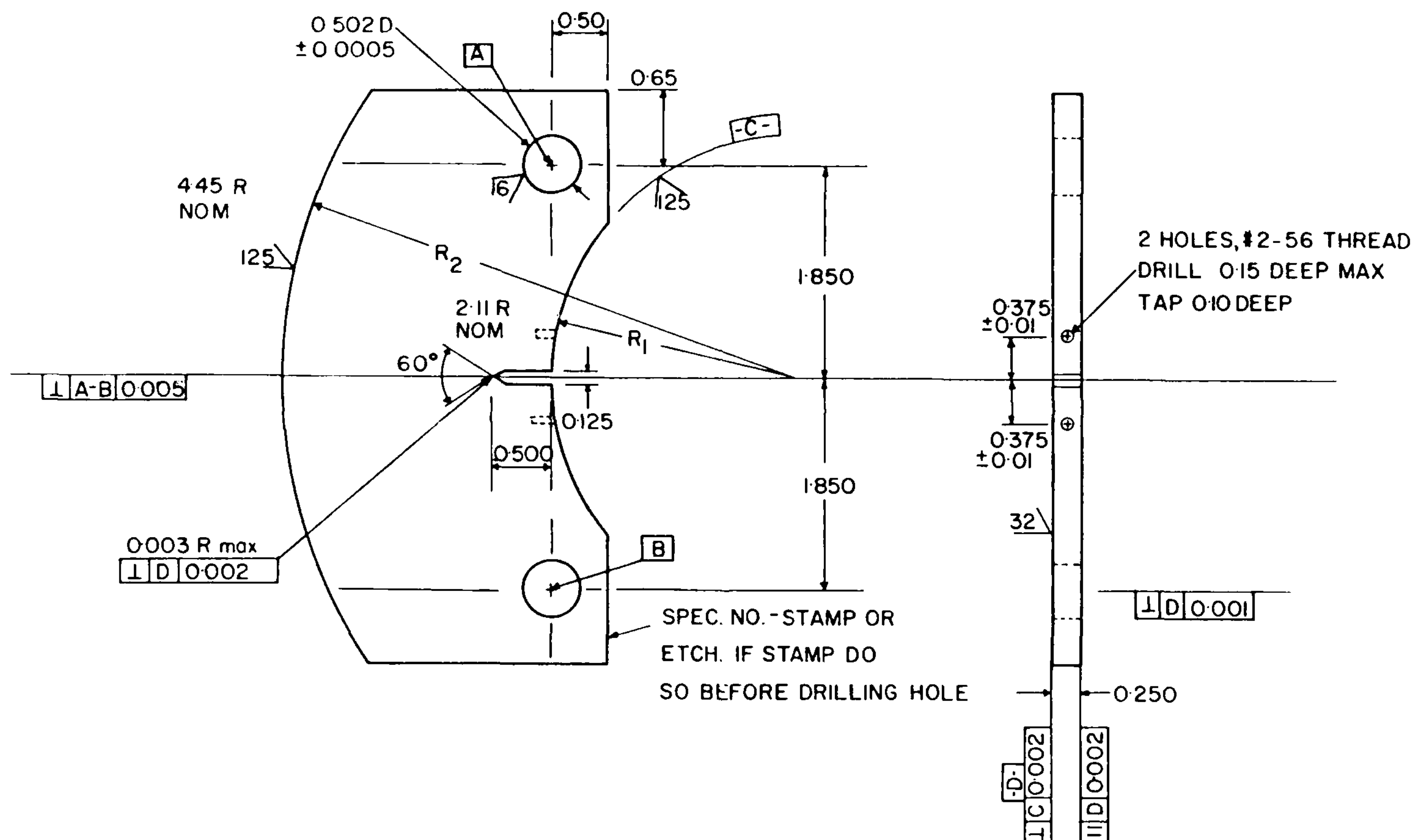

Figure 2: Fatigue crack growth specimen dimensions.

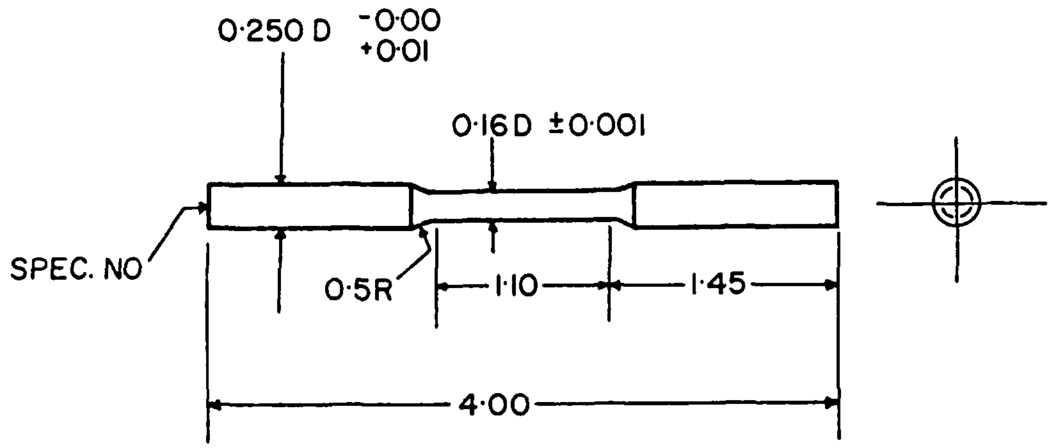

Figure 3: Tensile specimen dimensions.

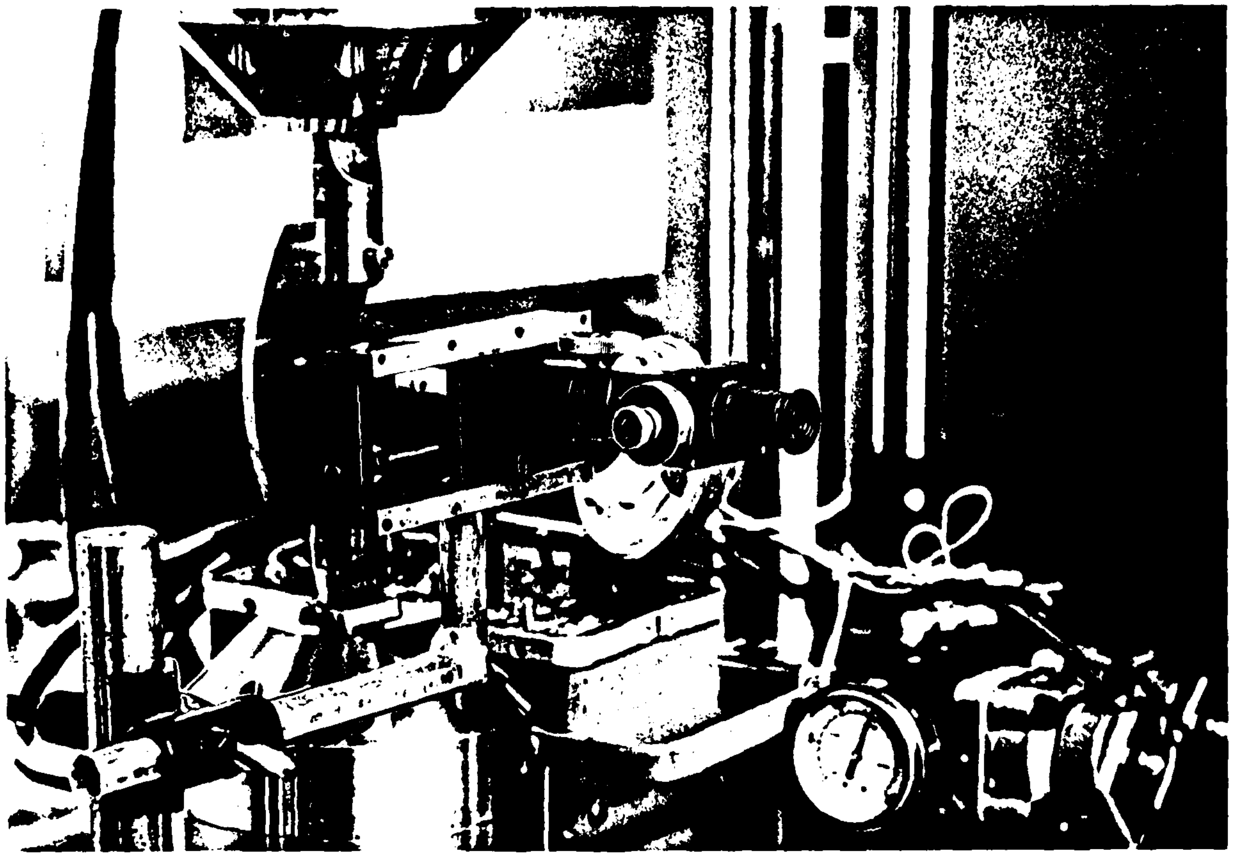

Figure 4: Arc-shaped specimen in MTS machine with a traveling microscope to measure crack length.

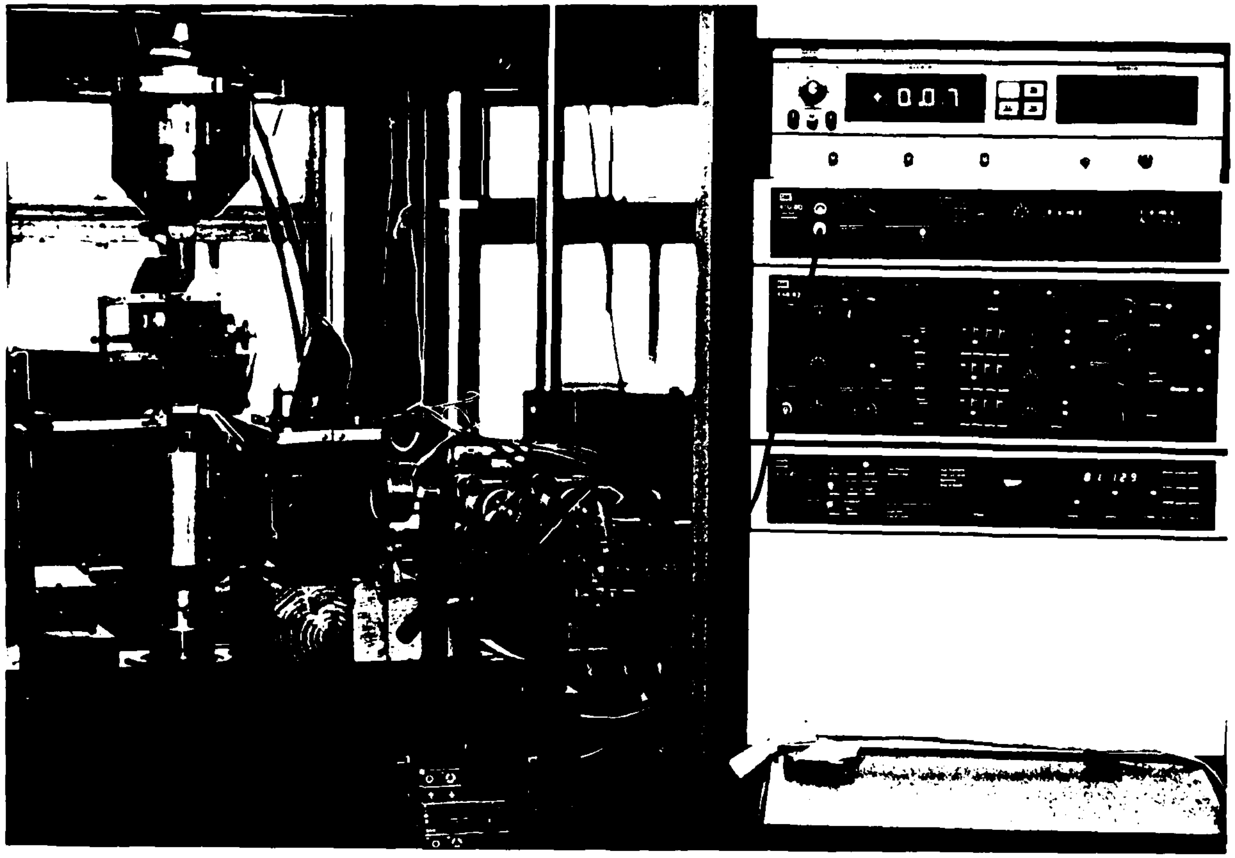

Figure 5: Laboratory ® MTS machine setup for fatigue crack growth tests.

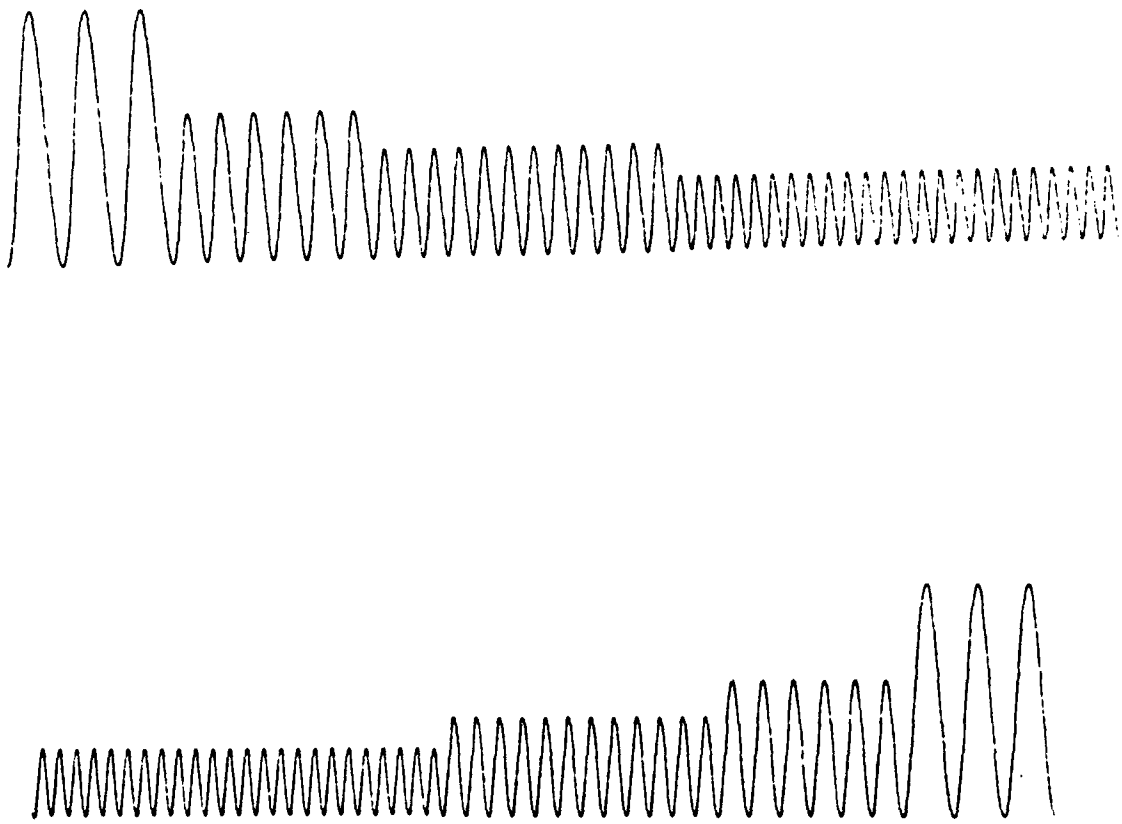

Figure 6: Graphical depiction of load history A as used in variable amplitude tests.

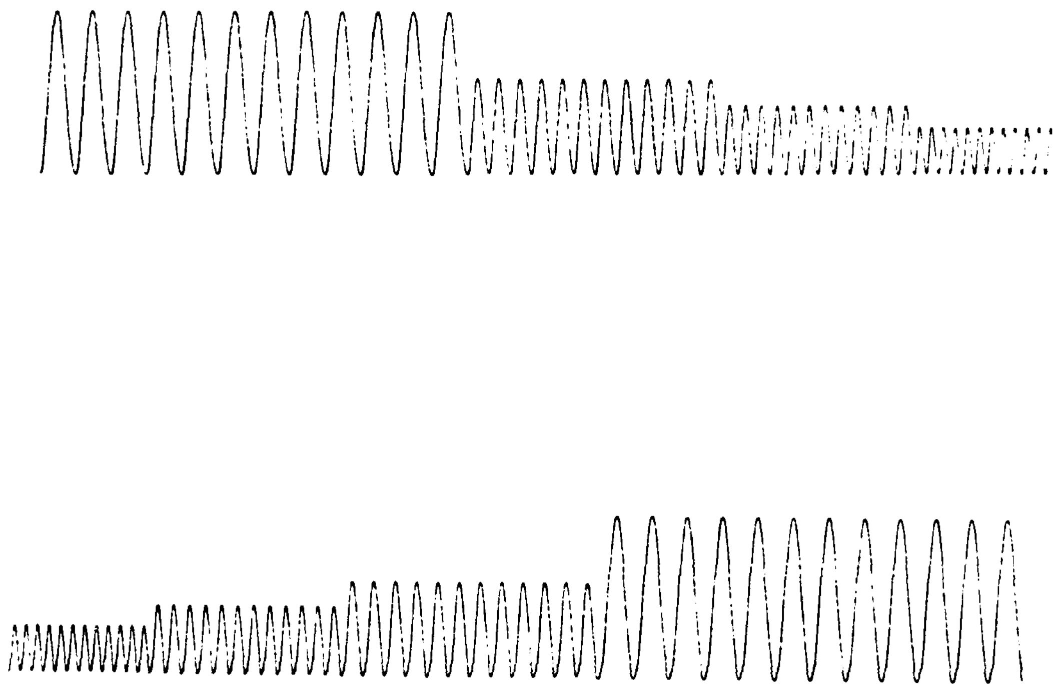

Figure 7: Graphical depiction of load history B as used in variable amplitude tests.

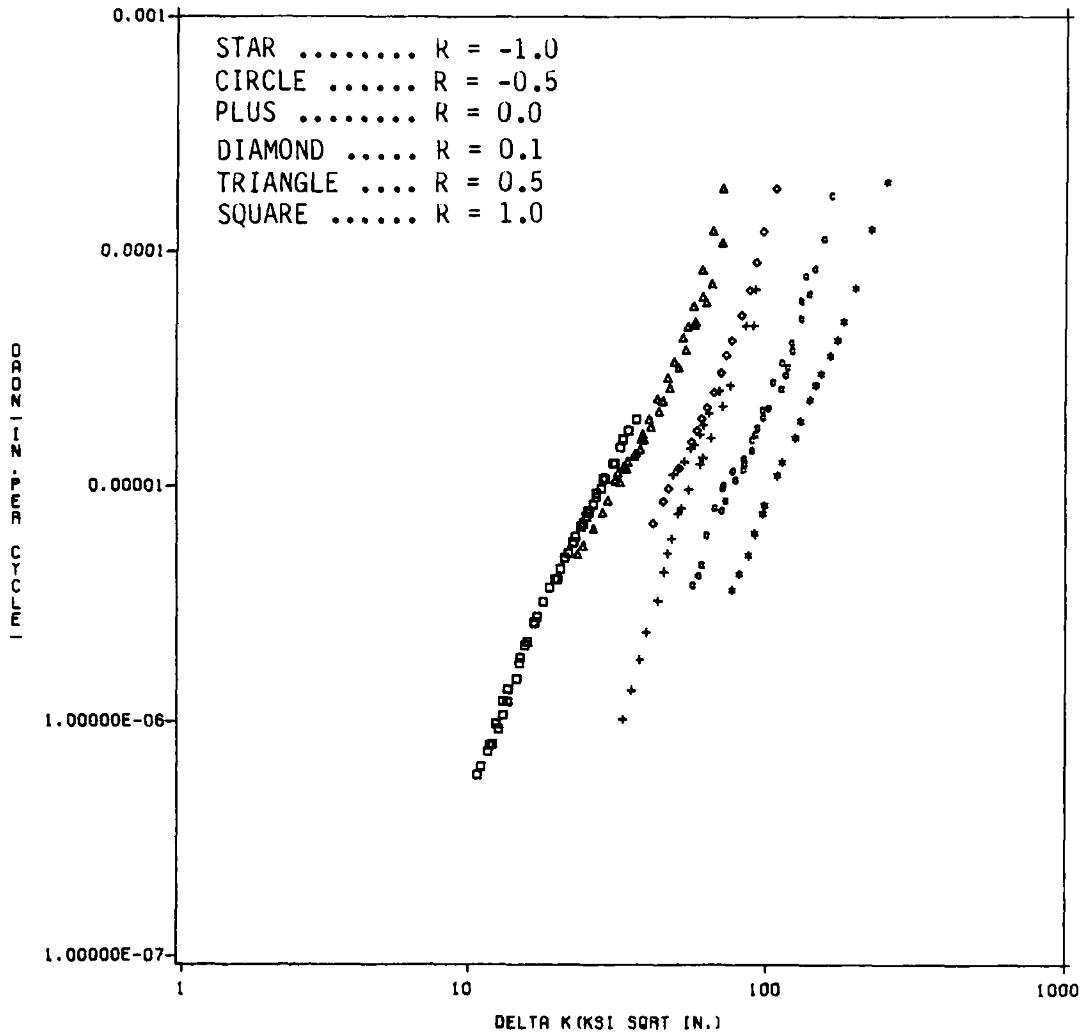

Figure 8: Crack growth rate versus change in stress intensity factor for 12 constant amplitude tests at various load ratios, R.

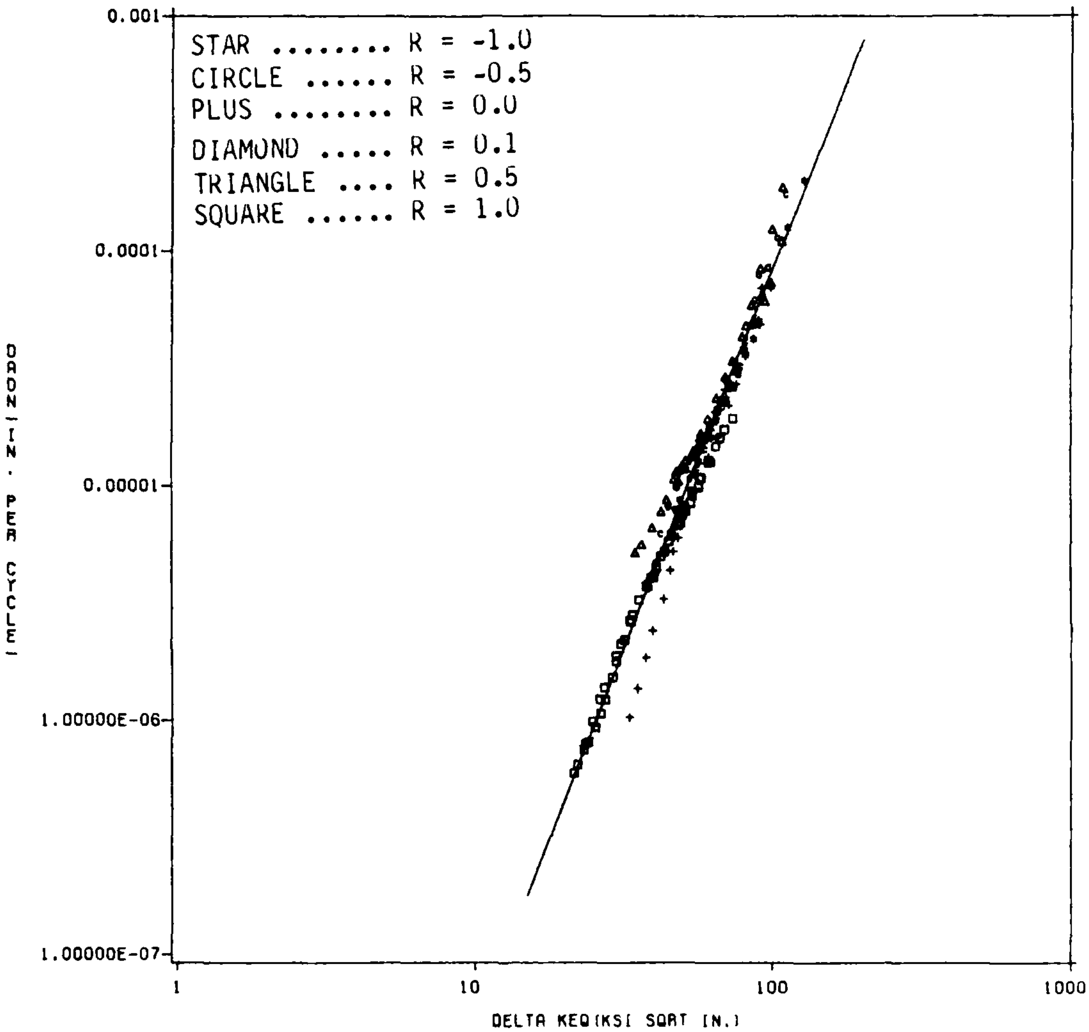

Figure 9: Crack Growth rate versus equivalent stress intensity factor range. Slope of fitted line is 3.24; y-intercept is 2.73×10^{-11}.

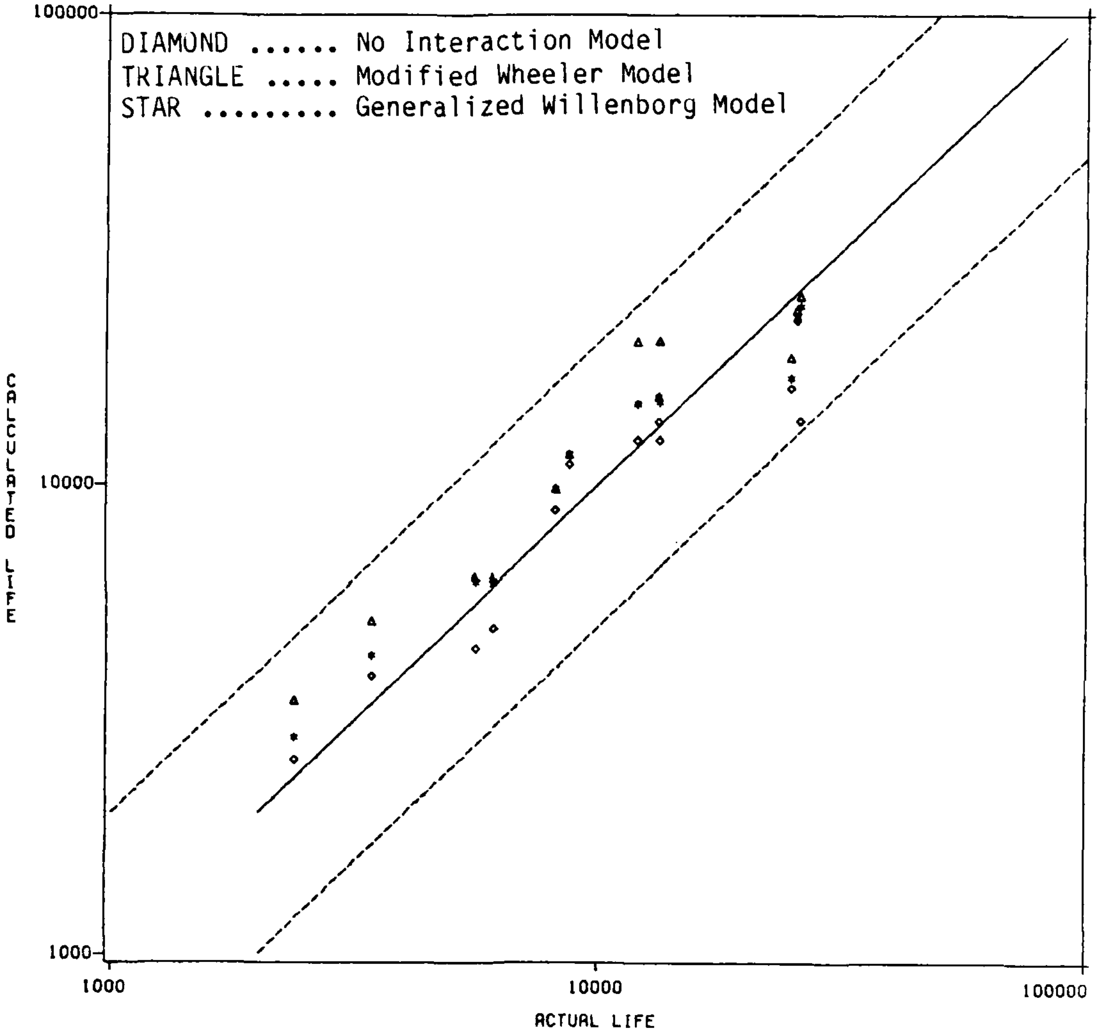

Figure 10: A comparison of crack life predictions to actual test life. Solid line is y = x and dotted lines are y = 2x and y = 0.5x.

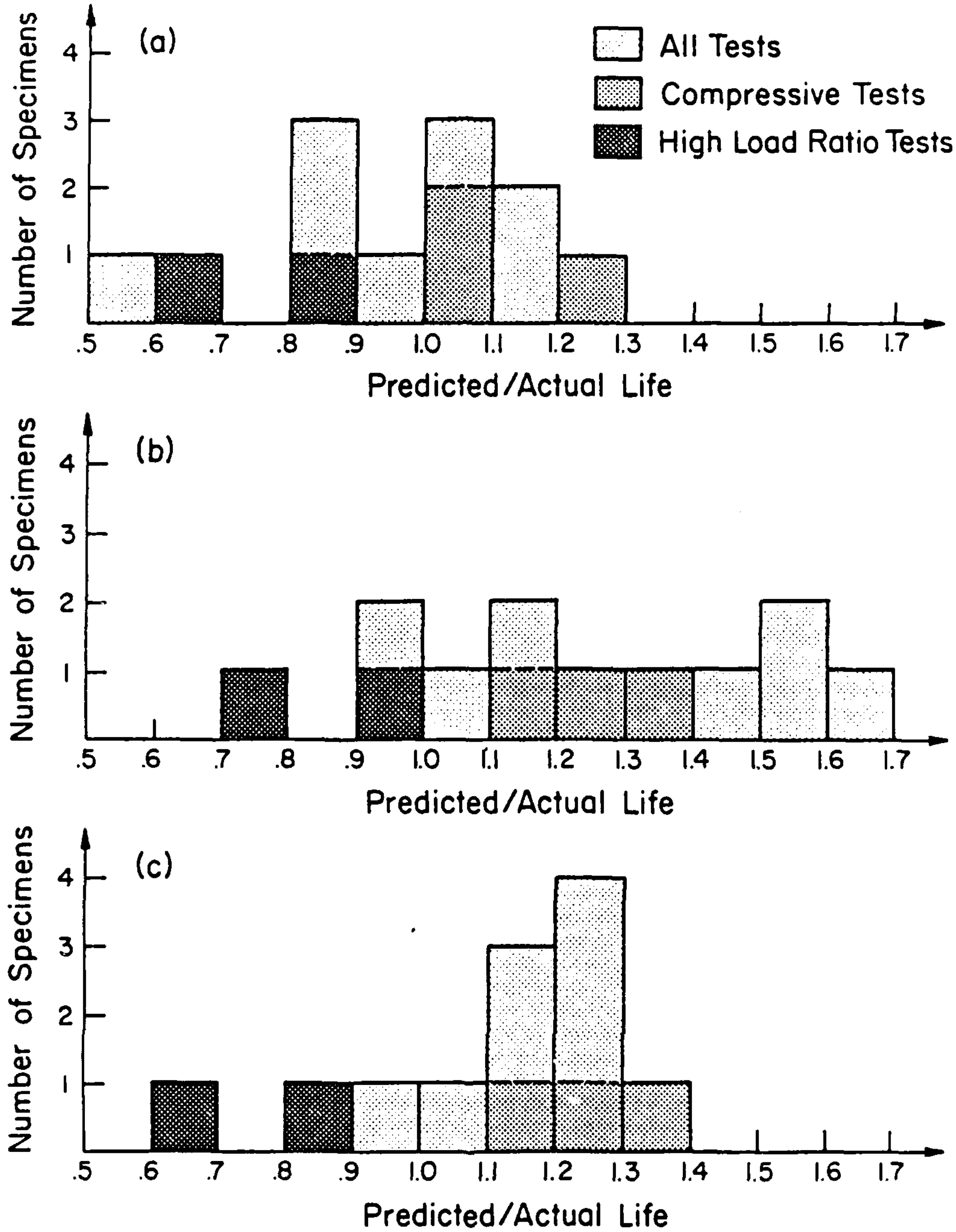

Figure 11: A histogram comparing life predictions to actual life for each of the three models:
a) No interaction b) Modified Wheeler
c) Generalized Willenborg.

DIAMOND .... Test Data
(———————) .... Wheeler Model
(- - - - - -) .... Willenborg Model
(—•—•—•—) .... No Interaction Model

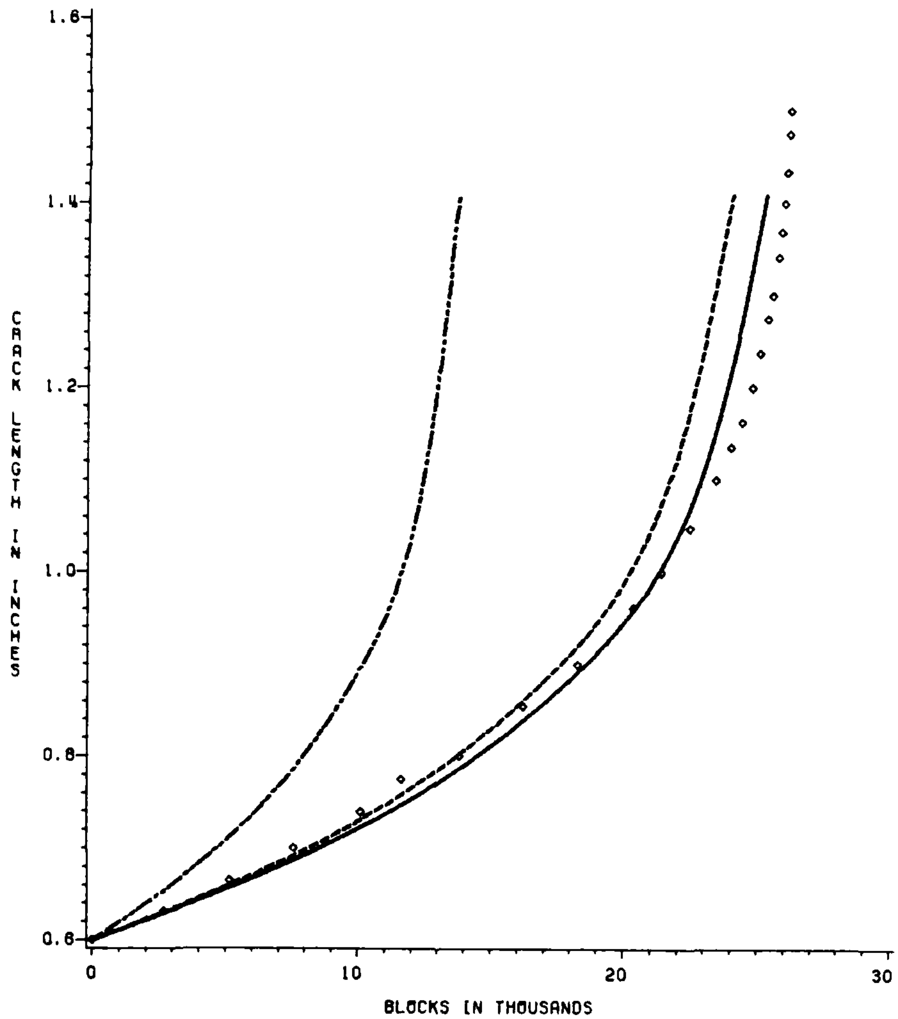

Figure 12: Crack growth data for specimen #15

DIAMOND .... Test Data
(———————) .... Wheeler Model
(- - - - - -) .... Willenborg Model
(—•—•—•—) .... No Interaction Model

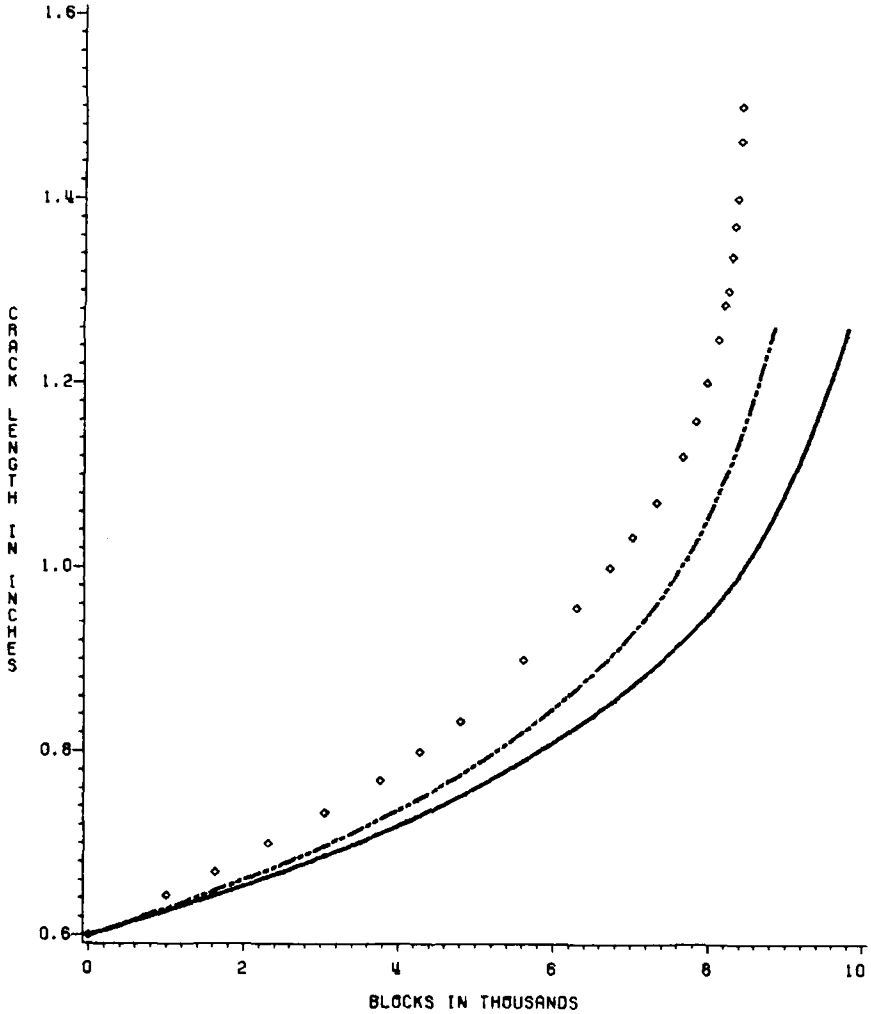

Figure 13: Crack growth data for specimen #13

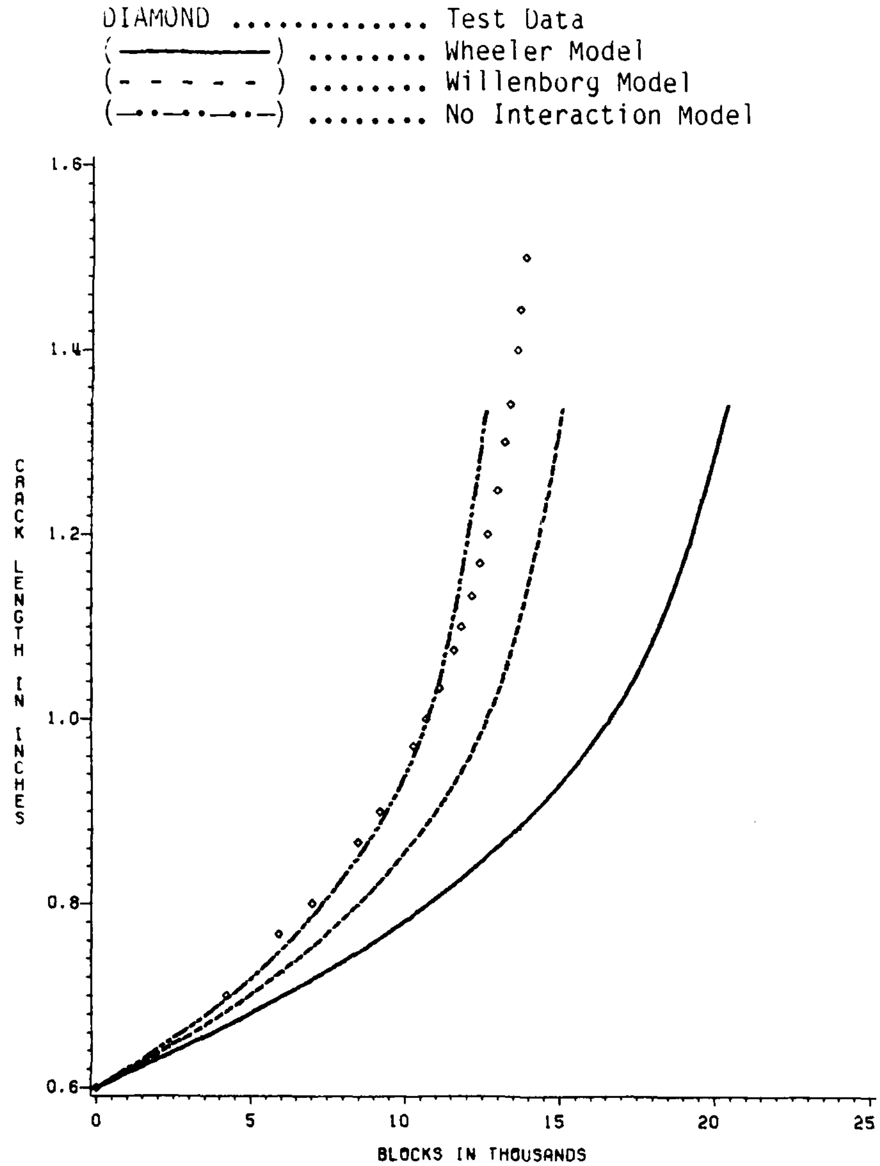

Figure 14: Crack growth data for specimen #9

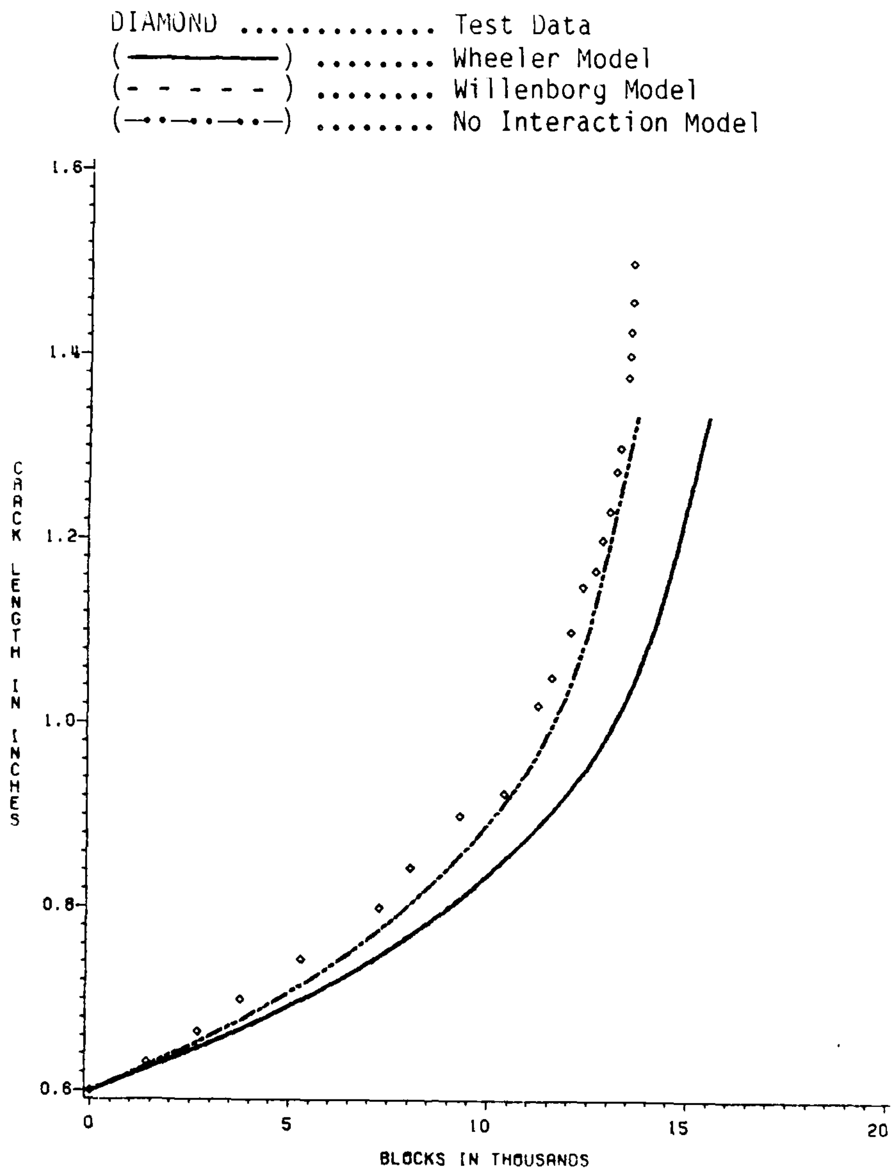

Figure 15: Crack growth data for specimen #1

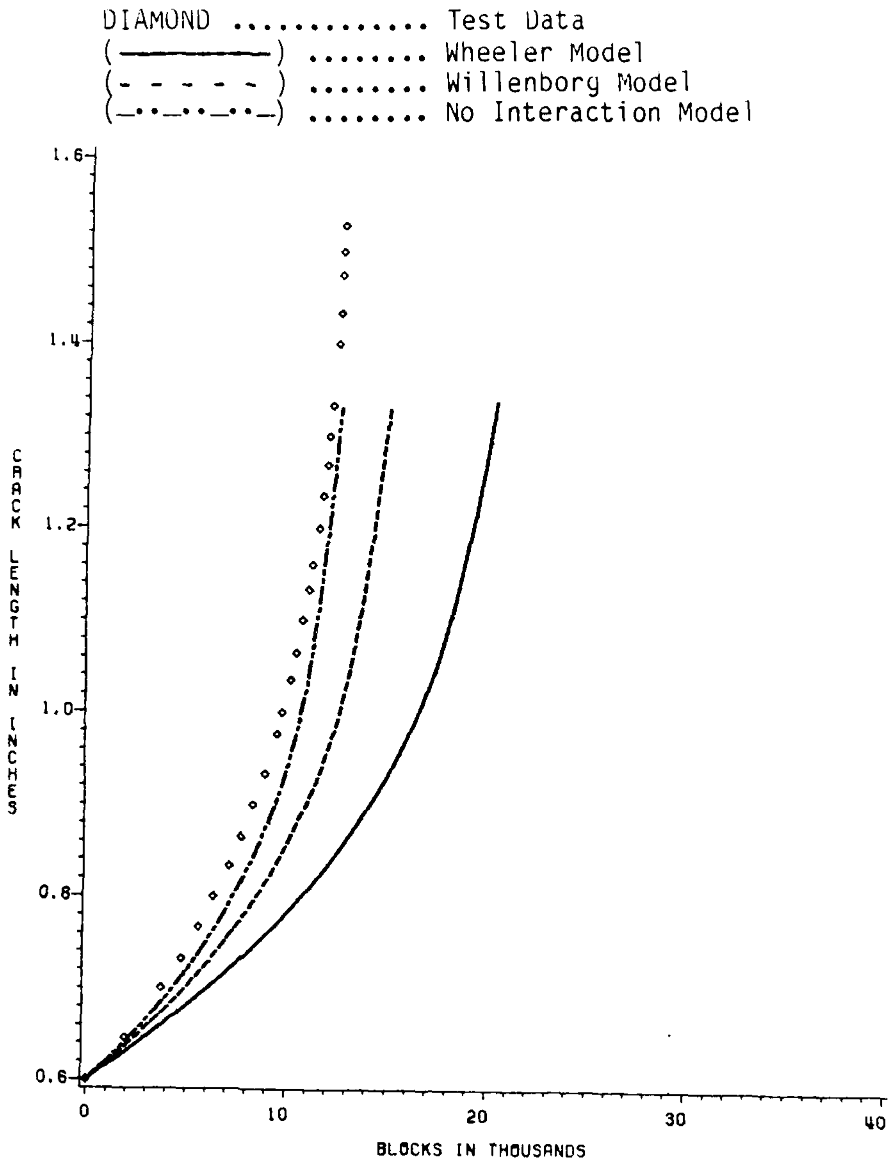

Figure 16: Crack growth data for specimen #22

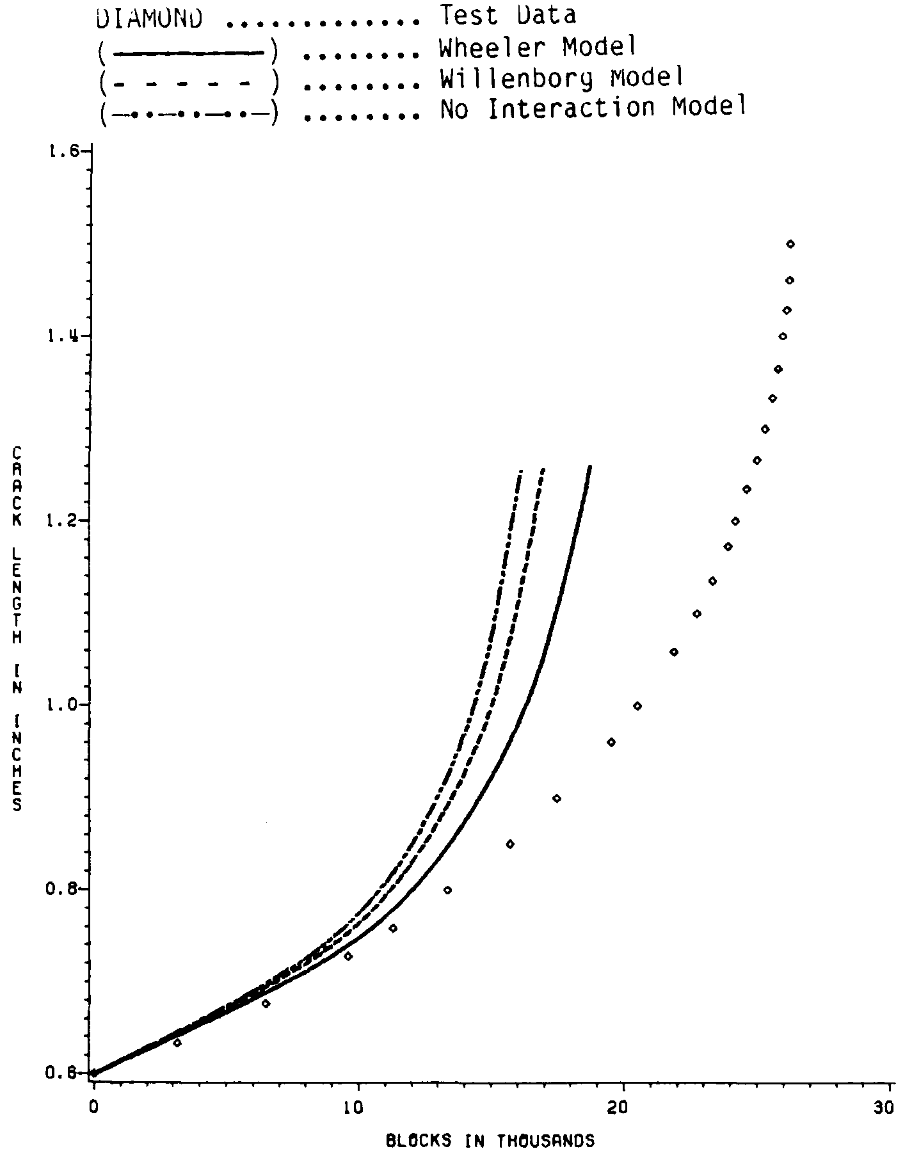

Figure 17: Crack growth data for specimen #30

DIAMOND .... Test Data
(————————) .... Wheeler Model
(- - - - - -) .... Willenborg Model
(—·—·—·—) .... No Interaction Model

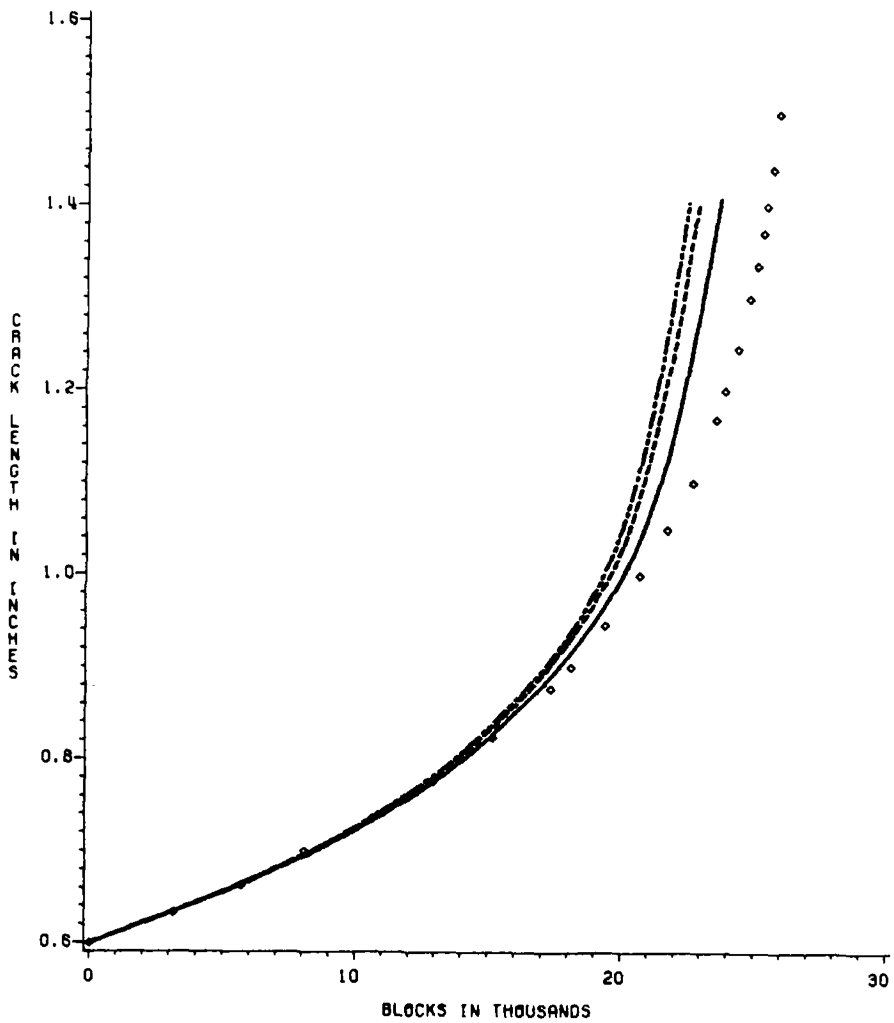

Figure 18: Crack growth data for specimen #10

DIAMOND .... Test Data
(————————) .... Wheeler Model
(- - - - - -) .... Willenborg Model
(—•—•—•—) .... No Interaction Model

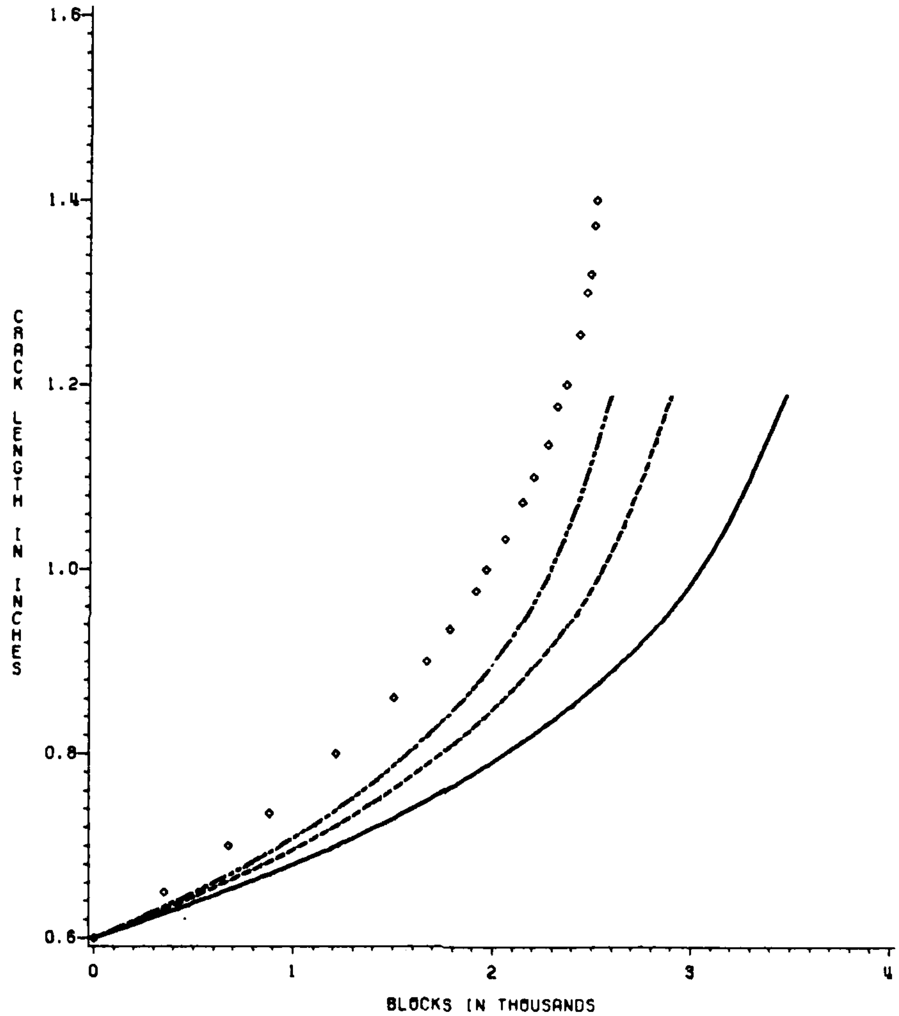

Figure 19: Crack growth data for specimen #26

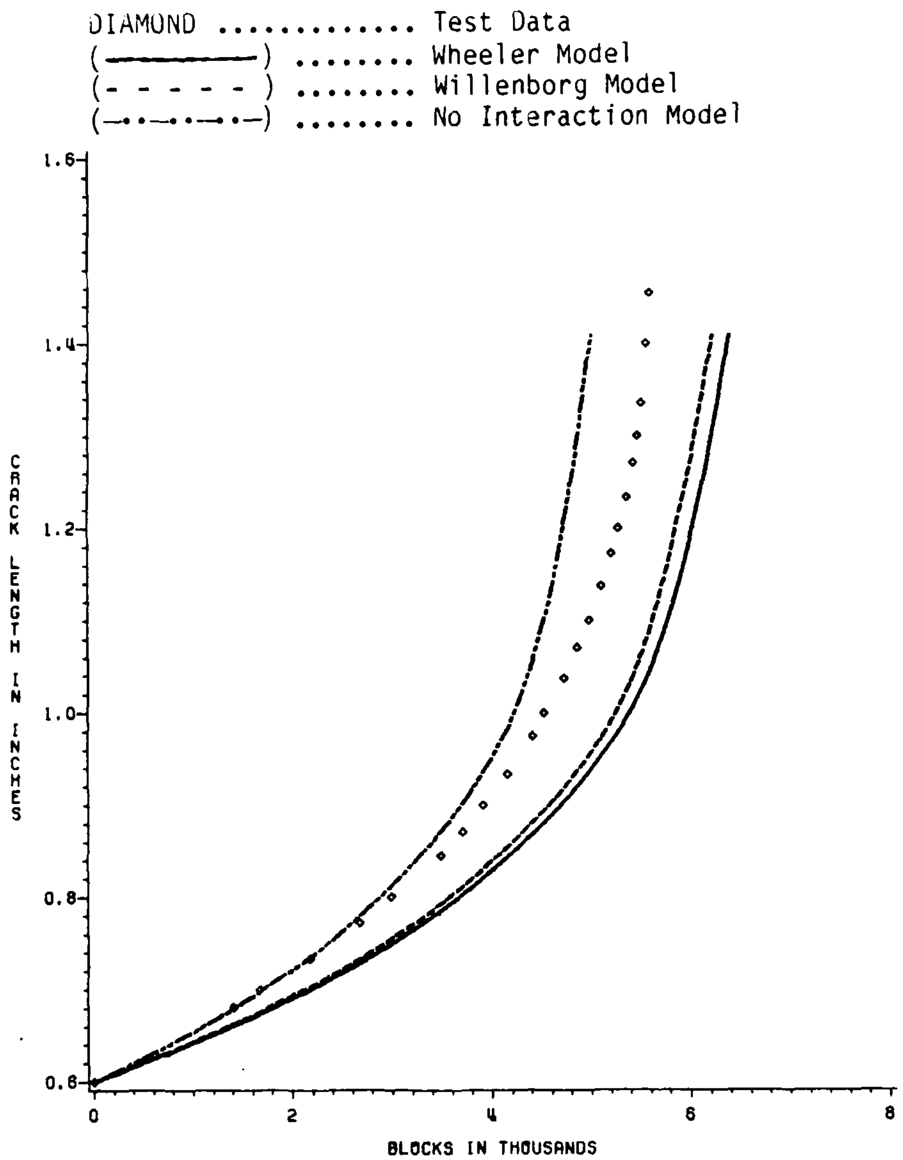

Figure 20: Crack growth data for specimen #7

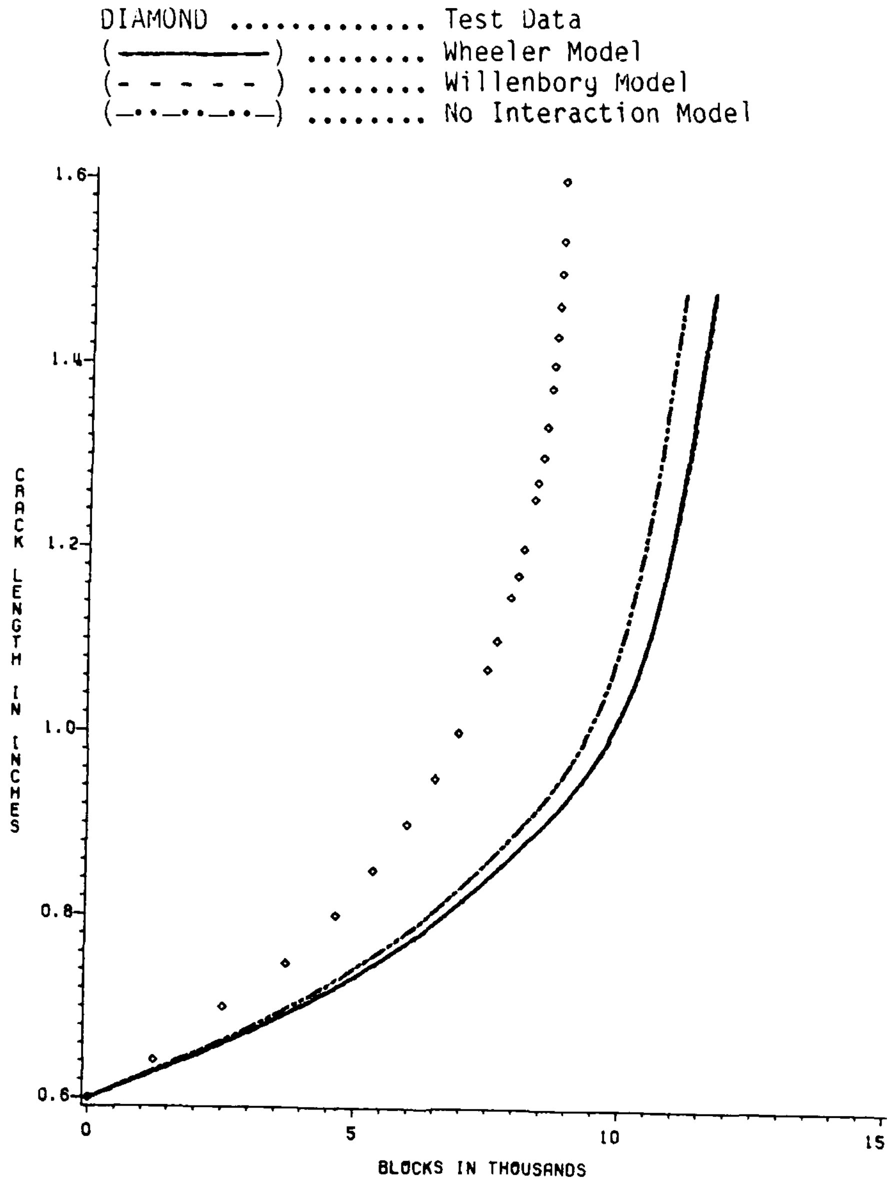

Figure 21: Crack growth data for specimen #28

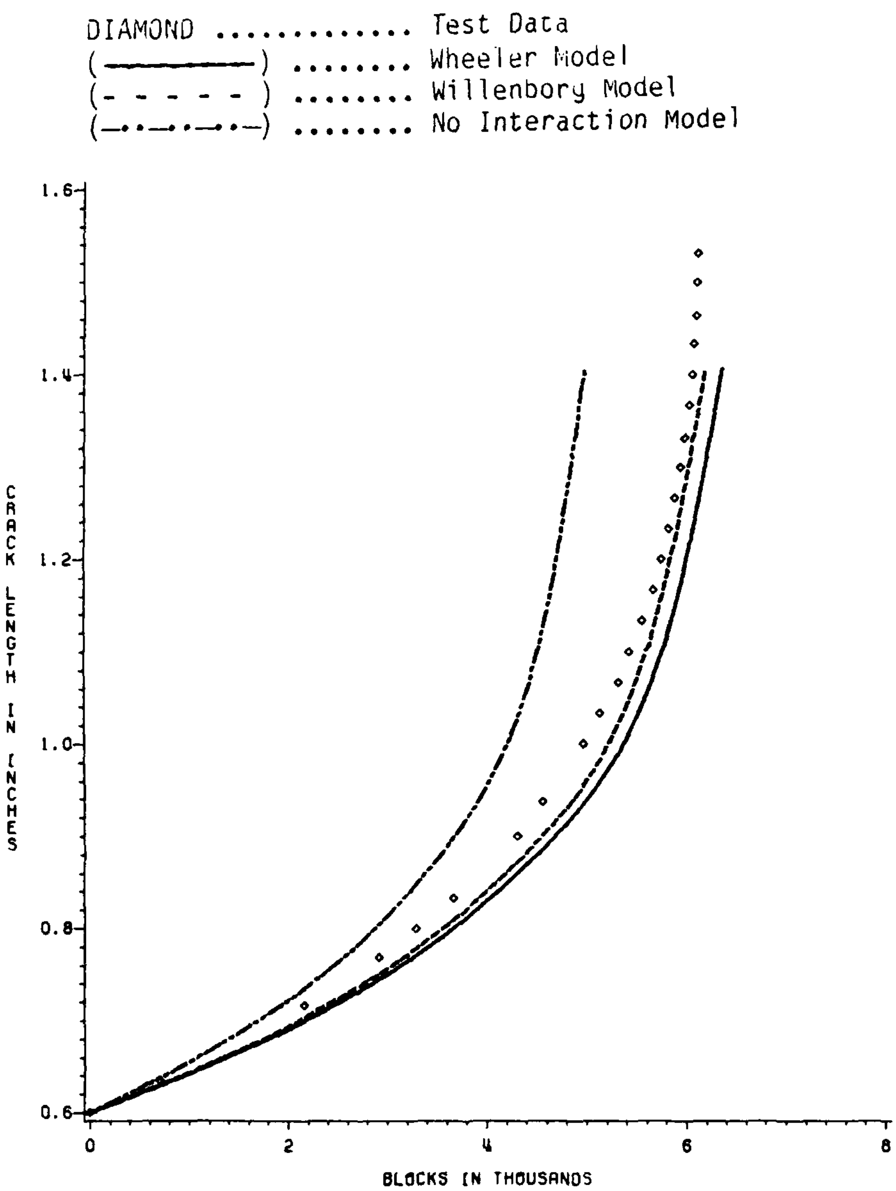

Figure 22: Crack growth data for specimen #29

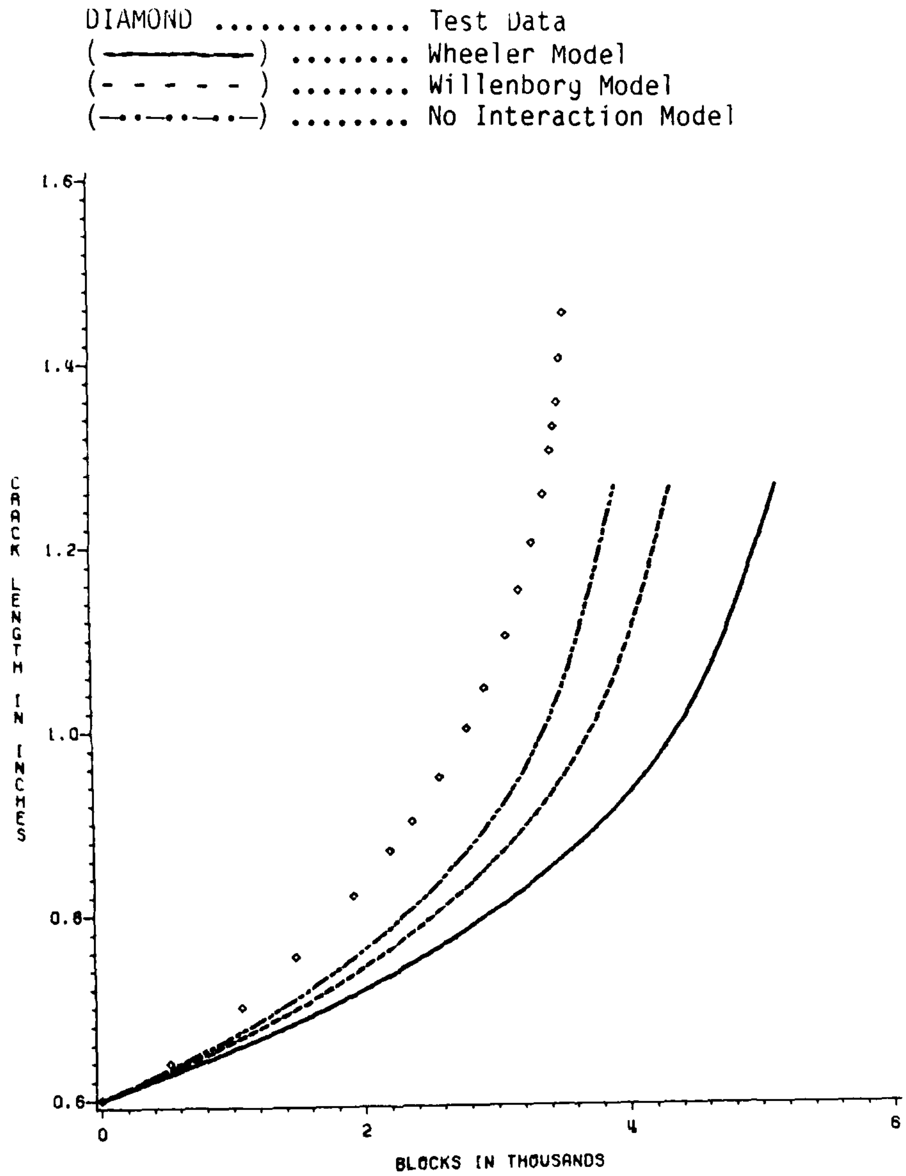

Figure 23: Crack growth data for specimen #17

IX. Tables

TABLE 1

FATIGUE CRACK

SPECIMEN DIMENSIONS

SPECIMEN NUMBERS	DIAMETERS BEFORE SPLIT INNER INCHES	OUTER INCHES	DIAMETERS AFTER SPLIT INNER INCHES	OUTER INCHES
1,2,3	4.240	8.898	4.319	8.984
5,6	4.240	9.898	4.320	8.986
7,8,9	4.240	8.898	4.319	8.892
10,11,12	4.240	8.898	4.318	8.981
13,15	4.240	8.898	4.320	8.982
16,17,18	4.240	8.898	4.321	8.982
19,20	4.240	8.898	4.321	8.982
22,23,24	4.245	8.898	4.327	8.982
26,27	4.245	8.898	4.325	8.982
28,29,30	4.245	8.898	4.325	8.982

TABLE 2

DESCRIPTION OF CONSTANT AMPLITUDE TESTS

SPECIMEN NUMBER	LOAD RATIO	MAXIMUM LOAD kips	MINIMUM LOAD kips
2	0.5	5.0	2.5
5	0.7	6.2	4.34
3	0.0	3.7	0.0
19	0.0	2.0	0.0
11	0.5	6.2	3.1
8	0.7	2.5	1.75
6	-0.5	2.5	-1.25
27	0.1	3.0	0.3
12	0.5	3.0	1.5
20	-1.0	2.5	-2.5
23	-0.5	3.0	-1.5
24	0.7	2.6	1.82

TABLE 3

VARIABLE AMPLITUDE HISTORIES

LEVEL NUMBER	$\frac{\Delta P}{\Delta P_{MAX}}$	NUMBER OF CYCLES HISTORY A	NUMBER OF CYCLES HISTORY B
1	1.00	3	12
2	0.60	6	12
3	0.45	12	12
4	0.33	24	12

NOTE: Histories A and B were also used in reversed order.

TABLE 4

DESCRIPTION OF VARIABLE AMPLITUDE TESTS

SPECIMEN NUMBER	LOAD HISTORY	MINIMUIM LOAD LEVEL (kips)	MAXIMUM LOAD LEVELS IN ORDER (kips)
15	A-Forward	0.0	3.0/1.8/1.35/1.0
13	A-Forward	-2.0	4.0/1.6/0.7/0.
9	A-Forward	1.75	3.5/2.8/2.54/2.33
1	A-Backward	-1.75	0.0/0.85*/1.4/3.5
22	A-Backward	1.75	2.33/2.54/2.8/3.0
30	A-Backward	2.8	3.2/3.34/3.52/4.0
10	B-Forward	2.1	3.0/2.64/2.51/2.3
26	B-Forward	2.25	4.5/3.6/3.26/3.0
7	B-Forward	0.0	3.0/1.8/1.35/1.00
28	B-Backward	-1.25	0.0/0.6*/1.0/2.5
29	B-Backward	0.0	1.0/1.35/1.8/3.0
17	B-Backward	2.0	2.67/2.9/3.2/4.0

*NOTE: Load readings were higher than programmed due to backlash in compressive loading of the specimen.

TABLE 5

A723 STEEL TENSILE DATA

QUANTITY	SPECIMEN NUMBER 14	SPECIMEN NUMBER 25	SPECIMEN NUMBER 4	SPECIMEN NUMBER 21	MEAN VALUE
Yield* Stress (ksi)	178.385	183.246	182.990	183.593	182.05
Young's Modulus (ksi)	29.852	31.061	32.216	29.512	30.66
Ultimate Strength (ksi)	184.896	189.791	188.144	190.104	188.23
True Fracture Strength (ksi)	180.380	161.017	196.667	190.000	182.02
%RA	17.71	7.33	22.68	21.9	17.41
% Elongation	5.69	6.67	8.94	9.51	7.70

* 0.2% offset

TABLE 6
CRACK GROWTH RATE AND STRESS INTENSITY DATA REDUCTION
INCREMENTAL POLYNOMIAL FOR DA/DN

SPECIMEN NUMBER 2--3 MARCH 86

ARC-SHAPED SPECIMEN
LOAD-TO-CRACK DISTANCE =0.0000 INCHES
R1 =2.1595INCHES R2 = 4.4920INCHES

DELTA P= 2.5000 KIPS PMIN= 2.5000 KIPS R= 0.5000
B= 0.2500 INCHES W= 2.3325 INCHES A0= 0.5000 INCHES
TESTING FREQUENCY= 10.0000 HERTZ

TOTAL CYCLES	CRACK LENGTH OBSERVED	CRACK LENGTH CALCULATED	Δ STRESS INTENSITY (KSI-$\sqrt{IN}$)	GROWTH RATE (IN/CYCLE)
12000.	0.5830			
14000.	0.6000			
15200.	0.6110			
16500.	0.6230	0.6260	31.27	1.068E-05
18000.	0.6440	0.6430	31.92	1.149E-05
21000.	0.6820	0.6781	33.30	1.231E-05
23000.	0.7000	0.7033	34.32	1.281E-05
26700.	0.7510	0.7514	36.35	1.387E-05
29500.	0.7930	0.7908	38.10	1.599E-05
30100.	0.8000	0.8001	38.53	1.674E-05
32800.	0.8430	0.8451	40.67	1.939E-05
35400.	0.9000	0.8972	43.34	2.376E-05
37700.	0.9530	0.9573	46.70	2.915E-05
39100.	1.0000	0.9991	49.26	3.412E-05
40600.	1.0500	1.0516	52.76	4.314E-05
41850.	1.1000	1.1076	56.92	5.881E-05
42680.	1.1470	1.1586	61.15	8.409E-05
43310.	1.2000	1.2138	66.29	1.239E-04
43700.	1.2510	1.2656	71.74	1.867E-04
43900.	1.3000			
44170.	1.3510			
44210.	1.4000			

TABLE 7
CRACK GROWTH RATE AND STRESS INTENSITY DATA REDUCTION
INCREMENTAL POLYNOMIAL FOR DA/DN

SPECIMEN NUMBER 3--4 MARCH 86

ARC-SHAPED SPECIMEN
LOAD-TO-CRACK DISTANCE =0.0000 INCHES
R1 =2.1595INCHES   R2 = 4.4920INCHES

DELTA P=   3.7000 KIPS   PMIN=   0.0000 KIPS   R= 0.0000
B= 0.2500 INCHES   W= 2.3325 INCHES   A0= 0.5000 INCHES
TESTING FREQUENCY= 10.0000 HERTZ

TOTAL CYCLES	CRACK LENGTH OBSERVED	CRACK LENGTH CALCULATED	Δ STRESS INTENSITY (KSI-$\sqrt{\text{IN}}$)	GROWTH RATE (IN/CYCLE)
14800.	0.6000			
16500.	0.6200			
18500.	0.6390			
21150.	0.6690	0.6678	48.68	1.129E-05
24030.	0.7000	0.7014	50.68	1.183E-05
27250.	0.7410	0.7406	53.11	1.288E-05
30560.	0.7870	0.7845	55.96	1.453E-05
31900.	0.8000	0.8042	57.30	1.510E-05
34200.	0.8390	0.8392	59.76	1.669E-05
36000.	0.8730	0.8686	61.93	1.825E-05
37730.	0.9000	0.9009	64.43	2.056E-05
40890.	0.9690	0.9656	69.85	2.576E-05
45700.	1.1000	1.1201	85.71	4.879E-05
46590.	1.1430	1.1670	91.59	6.964E-05
47380.	1.2000			
48350.	1.3000			
49000.	1.4000			

TABLE 8

CRACK GROWTH RATE AND STRESS INTENSITY DATA REDUCTION
INCREMENTAL POLYNOMIAL FOR DA/DN

SPECIMEN NUMBER 5--4 MARCH 86

ARC-SHAPED SPECIMEN
LOAD-TO-CRACK DISTANCE =0.0000 INCHES
R1 =2.1600INCHES R2 = 4.4930INCHES

DELTA P= 1.8600 KIPS PMIN= 4.3400 KIPS R= 0.7000
B= 0.2500 INCHES W= 2.3330 INCHES A0= 0.5000 INCHES
TESTING FREQUENCY= 10.0000 HERTZ

TOTAL CYCLES	CRACK LENGTH OBSERVED	CRACK LENGTH CALCULATED	Δ STRESS INTENSITY (KSI-$\sqrt{IN}$)	GROWTH RATE (IN/CYCLE)
23500.	0.5681			
29550.	0.6000			
35700.	0.6330			
40440.	0.6630	0.6650	24.39	6.929E-06
44980.	0.7000	0.6968	25.33	7.752E-06
50840.	0.7450	0.7444	26.81	9.080E-06
57040.	0.8000	0.8041	28.79	1.079E-05
61200.	0.8510	0.8497	30.42	1.257E-05
65000.	0.9000	0.8994	32.32	1.473E-05
68400.	0.9470	0.9512	34.47	1.737E-05
71200.	1.0000	1.0007	36.71	1.940E-05
73450.	1.0470			
75610.	1.1000			
76820.	1.1200			

TABLE 9
CRACK GROWTH RATE AND STRESS INTENSITY DATA REDUCTION
INCREMENTAL POLYNOMIAL FOR DA/DN

SPECIMEN NUMBER 13--12 MAR 86

ARC-SHAPED SPECIMEN
LOAD-TO-CRACK DISTANCE =0.0000 INCHES
R1 =2.1600INCHES R2 = 4.4910INCHES

DELTA P= 2.0000 KIPS PMIN= 0.0000 KIPS R= 0.0000
B= 0.2500 INCHES W= 2.3310 INCHES A0= 0.6000 INCHES
TESTING FREQUENCY= 10.0000 HERTZ

TOTAL CYCLES	CRACK LENGTH OBSERVED	CRACK LENGTH CALCULATED	Δ STRESS INTENSITY (KSI-$\sqrt{IN}$)	GROWTH RATE (IN/CYCLE)
206000.	0.7000			
273100.	0.7370			
374200.	0.8000			
438900.	0.8530	0.8553	32.97	1.027E-06
487600.	0.9000	0.9084	35.19	1.369E-06
525600.	0.9530	0.9605	37.55	1.847E-06
550800.	1.0000	1.0069	39.85	2.423E-06
574600.	1.0630	1.0699	43.31	3.286E-06
585100.	1.1000	1.1066	45.53	4.342E-06
589300.	1.1240	1.1241	46.65	5.231E-06
593600.	1.1450	1.1456	48.08	6.020E-06
599100.	1.1790	1.1799	50.51	7.668E-06
601600.	1.2000	1.1987	51.93	8.159E-06
605800.	1.2330	1.2355	54.88	9.749E-06
611100.	1.2980	1.2920	59.94	1.244E-05
612200.	1.3000	1.3051	61.21	1.333E-05
615000.	1.3430	1.3433	65.19	1.614E-05
618500.	1.4000	1.3999	71.88	2.199E-05
619800.	1.4280	1.4294	75.79	2.715E-05
622600.	1.5000	1.5220	90.56	4.872E-05
623500.	1.5450			
624400.	1.6000			
624970.	1.7000			

TABLE 10
CRACK GROWTH RATE AND STRESS INTENSITY DATA REDUCTION
INCREMENTAL POLYNOMIAL FOR DA/DN

SPECIMEN NUMBER 11-- 14 MAR 86

ARC-SHAPED SPECIMEN
LOAD-TO-CRACK DISTANCE =0.0000 INCHES
R1 =2.1590INCHES R2 = 4.4905INCHES

DELTA P= 3.1000 KIPS PMIN= 3.1000 KIPS R= 0.5000
B= 0.2500 INCHES W= 2.3315 INCHES A0= 0.6000 INCHES
TESTING FREQUENCY= 10.0000 HERTZ

TOTAL CYCLES	CRACK LENGTH OBSERVED	CRACK LENGTH CALCULATED	Δ STRESS INTENSITY (KSI-$\sqrt{IN}$)	GROWTH RATE (IN/CYCLE)
8970.	0.6728			
10210.	0.8000			
12450.	0.8690			
13200.	0.9000	0.9085	54.53	4.825E-05
14400.	0.9480	0.9548	57.77	5.069E-05
15670.	1.0330	1.0242	63.15	6.115E-05
16200.	1.0550	1.0575	66.00	7.348E-05
16900.	1.1000	1.1130	71.17	1.102E-04
17450.	1.1490			
17700.	1.2000			
18060.	1.3000			

TABLE 11
CRACK GROWTH RATE AND STRESS INTENSITY DATA REDUCTION
INCREMENTAL POLYNOMIAL FOR DA/DN

SPECIMEN NUMBER 8--18 MARCH 86

ARC-SHAPED SPECIMEN
LOAD-TO-CRACK DISTANCE =0.0000 INCHES
R1 =2.1595INCHES R2 = 4.4910INCHES

DELTA P= 0.7500 KIPS PMIN= 1.7500 KIPS R= 0.7000
B= 0.2500 INCHES W= 2.3315 INCHES A0= 0.6000 INCHES
TESTING FREQUENCY= 10.0000 HERTZ

TOTAL CYCLES	CRACK LENGTH OBSERVED	CRACK LENGTH CALCULATED	Δ STRESS INTENSITY (KSI-$\sqrt{IN}$)	GROWTH RATE (IN/CYCLE)
76000.	0.6295			
123860.	0.6531			
213500.	0.7000			
278880.	0.7350	0.7371	10.73	5.945E-07
321550.	0.7650	0.7625	11.06	6.500E-07
380320.	0.8000	0.8015	11.59	7.496E-07
400000.	0.8140	0.8150	11.77	7.995E-07
450000.	0.8570	0.8557	12.37	9.802E-07
493900.	0.9000	0.9008	13.07	1.221E-06
518760.	0.9310	0.9323	13.59	1.383E-06
564560.	1.0000	1.0017	14.84	1.786E-06
589960.	1.0490	1.0497	15.80	2.208E-06
606570.	1.0810	1.0886	16.65	2.633E-06
611100.	1.1000	1.0984	16.87	2.826E-06
623700.	1.1370	1.1355	17.77	3.253E-06
634500.	1.1730	1.1733	18.75	3.744E-06
641750.	1.2000	1.2004	19.51	4.065E-06
653800.	1.2510	1.2522	21.10	5.007E-06
660650.	1.2870	1.2873	22.29	5.814E-06
663000.	1.3000	1.3003	22.76	6.132E-06
672600.	1.3630	1.3637	25.29	7.887E-06
677050.	1.4000	1.3986	26.87	9.398E-06
680300.	1.4280	1.4305	28.46	1.084E-05
686850.	1.5000	1.5093	33.08	1.603E-05
689200.	1.5430			
690100.	1.5630			
691250.	1.6000			

TABLE 12
CRACK GROWTH RATE AND STRESS INTENSITY DATA REDUCTION
INCREMENTAL POLYNOMIAL FOR DA/DN

SPECIMEN NUMBER 6--21 MARCH 86

ARC-SHAPED SPECIMEN
LOAD-TO-CRACK DISTANCE =0.0000 INCHES
R1 =2.1600INCHES R2 = 4.4930INCHES

DELTA P= 3.7500 KIPS PMIN= -1.2500 KIPS R=-0.5000
B= 0.2500 INCHES W= 2.3330 INCHES A0= 0.6250 INCHES
TESTING FREQUENCY= 10.0000 HERTZ

TOTAL CYCLES	CRACK LENGTH OBSERVED	CRACK LENGTH CALCULATED	Δ STRESS INTENSITY (KSI-$\sqrt{IN}$)	GROWTH RATE (IN/CYCLE)
11150.	0.6585			
26850.	0.7000			
42200.	0.7440			
54680.	0.8000	0.7849	56.73	3.828E-06
64440.	0.8040	0.8221	59.32	4.189E-06
69550.	0.8280	0.8419	60.75	4.662E-06
76360.	0.9000	0.8712	62.95	6.191E-06
83070.	0.9040	0.9219	67.00	8.123E-06
89030.	0.9510	0.9727	71.40	9.797E-06
90350.	1.0000	0.9792	72.00	1.005E-05
94370.	1.0360	1.0322	77.11	1.166E-05
99340.	1.0890	1.0931	83.65	1.180E-05
100270.	1.1000	1.0994	84.38	1.251E-05
103390.	1.1380	1.1404	89.33	1.421E-05
105000.	1.1630	1.1600	91.85	1.665E-05
107150.	1.2000	1.1978	97.05	2.117E-05
109500.	1.2380	1.2494	104.88	2.769E-05
111100.	1.3000	1.2959	112.83	3.364E-05
112360.	1.3440	1.3407	121.41	4.093E-05
113300.	1.3790	1.3810	130.03	6.155E-05
113800.	1.4000	1.4006	134.59	7.872E-05
114650.	1.4510			
115800.	1.6000			
116050.	1.7000			

TABLE 13
CRACK GROWTH RATE AND STRESS INTENSITY DATA REDUCTION
INCREMENTAL POLYNOMIAL FOR DA/DN

SPECIMEN NUMBER 27-22 MARCH 86

ARC-SHAPED SPECIMEN
LOAD-TO-CRACK DISTANCE =0.0000 INCHES
R1 =2.1625INCHES R2 = 4.4910INCHES

DELTA P= 2.7000 KIPS PMIN= 0.3000 KIPS R= 0.1000
B= 0.2500 INCHES W= 2.3285 INCHES A0= 0.6000 INCHES
TESTING FREQUENCY= 10.0000 HERTZ

TOTAL CYCLES	CRACK LENGTH OBSERVED	CRACK LENGTH CALCULATED	Δ STRESS INTENSITY (KSI-$\sqrt{IN}$)	GROWTH RATE (IN/CYCLE)
12260.	0.6453			
23500.	0.7000			
32900.	0.7590			
40300.	0.8000	0.8013	41.77	6.977E-06
49210.	0.8610	0.8656	45.15	8.683E-06
53500.	0.9000	0.9000	47.09	9.804E-06
59370.	0.9590	0.9614	50.85	1.200E-05
65500.	1.0390	1.0417	56.42	1.553E-05
67400.	1.0670	1.0712	58.69	1.734E-05
69000.	1.1000	1.0991	60.96	1.948E-05
70510.	1.1310	1.1285	63.51	2.186E-05
72000.	1.1590	1.1622	66.63	2.515E-05
73550.	1.2000	1.2019	70.60	3.065E-05
74480.	1.2310	1.2304	73.69	3.642E-05
75200.	1.2570	1.2572	76.80	4.217E-05
76240.	1.3000	1.3032	82.61	5.403E-05
76950.	1.3410	1.3428	88.19	6.911E-05
77350.	1.3690	1.3713	92.57	9.101E-05
77700.	1.4000	1.4010	97.52	1.222E-04
78130.	1.4410	1.4546	107.57	1.868E-04
78400.	1.5000			
78560.	1.5510			
78680.	1.5930			

TABLE 14
CRACK GROWTH RATE AND STRESS INTENSITY DATA REDUCTION
INCREMENTAL POLYNOMIAL FOR DA/DN

SPECIMEN NUMBER 12-23 MARCH 86

ARC-SHAPED SPECIMEN
LOAD-TO-CRACK DISTANCE =0.0000 INCHES
R1 =2.1590INCHES R2 = 4.4905INCHES

DELTA P= 1.5000 KIPS PMIN= 1.5000 KIPS R= 0.5000
B= 0.2500 INCHES W= 2.3315 INCHES A0= 0.6000 INCHES
TESTING FREQUENCY= 10.0000 HERTZ

TOTAL CYCLES	CRACK LENGTH OBSERVED	CRACK LENGTH CALCULATED	Δ STRESS INTENSITY (KSI-$\sqrt{IN}$)	GROWTH RATE (IN/CYCLE)
18020.	0.6335			
31900.	0.7000			
44900.	0.7510			
55770.	0.8000	0.8052	23.27	5.186E-06
63310.	0.8490	0.8422	24.33	5.652E-06
74000.	0.9000	0.9057	26.29	6.653E-06
82300.	0.9610	0.9626	28.23	7.763E-06
87000.	1.0000	0.9978	29.53	8.737E-06
94240.	1.0630	1.0669	32.34	1.053E-05
97560.	1.1000	1.1010	33.87	1.189E-05
101190.	1.1450	1.1458	36.06	1.356E-05
103660.	1.1800	1.1806	37.91	1.448E-05
104880.	1.2000	1.1982	38.90	1.582E-05
107290.	1.2370	1.2372	41.24	1.801E-05
109370.	1.2690	1.2754	43.76	2.112E-05
110300.	1.3000	1.2949	45.13	2.320E-05
111600.	1.3260	1.3261	47.48	2.635E-05
113130.	1.3670	1.3690	51.04	3.213E-05
114100.	1.4000	1.3992	53.80	3.835E-05
115100.	1.4350	1.4401	57.93	4.906E-05
115750.	1.4710	1.4713	61.42	6.485E-05
116240.	1.5000			
116900.	1.5490			
117220.	1.6000			

TABLE 15
CRACK GROWTH RATE AND STRESS INTENSITY DATA REDUCTION
INCREMENTAL POLYNOMIAL FOR DA/DN

SPECIMEN NUMBER 20-23 MARCH 86

ARC-SHAPED SPECIMEN
LOAD-TO-CRACK DISTANCE =0.0000 INCHES
R1 =2.1605INCHES R2 = 4.4910INCHES

DELTA P= 5.0000 KIPS PMIN= -2.5000 KIPS R=-1.0000
B= 0.2500 INCHES W= 2.3305 INCHES A0= 0.6000 INCHES
TESTING FREQUENCY= 10.0000 HERTZ

TOTAL CYCLES	CRACK LENGTH OBSERVED	CRACK LENGTH CALCULATED	Δ STRESS INTENSITY (KSI-$\sqrt{IN}$)	GROWTH RATE (IN/CYCLE)
25150.	0.6571			
43900.	0.7000			
59810.	0.7470			
75290.	0.8000	0.7984	76.99	3.669E-06
87120.	0.8410	0.8432	81.25	4.275E-06
100350.	0.9000	0.9025	87.36	5.133E-06
107660.	0.9370	0.9394	91.45	6.347E-06
115150.	0.9870	0.9894	97.44	7.668E-06
116950.	1.0000	0.9996	98.73	8.313E-06
125100.	1.0750	1.0759	109.20	1.120E-05
127580.	1.1000	1.1013	113.04	1.276E-05
132440.	1.1670	1.1706	124.65	1.615E-05
134350.	1.2000	1.1998	130.09	1.903E-05
136700.	1.2450	1.2483	139.98	2.337E-05
137820.	1.2710	1.2730	145.45	2.718E-05
138800.	1.3000	1.2997	151.79	3.022E-05
140160.	1.3430	1.3434	163.09	3.617E-05
141070.	1.3790	1.3774	172.84	4.204E-05
141660.	1.4000	1.4007	180.03	5.029E-05
142650.	1.4490	1.4508	197.27	7.042E-05
143500.	1.5000	1.5145	223.15	1.247E-04
143920.	1.5570	1.5745	252.80	1.990E-04
144160.	1.6000			
144550.	1.7000			
144670.	1.8000			

TABLE 16
CRACK GROWTH RATE AND STRESS INTENSITY DATA REDUCTION
INCREMENTAL POLYNOMIAL FOR DA/DN

SPECIMEN NUMBER 23-6 APRIL 86

ARC-SHAPED SPECIMEN
LOAD-TO-CRACK DISTANCE =0.0000 INCHES
R1 =2.1635INCHES R2 = 4.4910INCHES

DELTA P= 4.5000 KIPS PMIN= -1.5000 KIPS R=-0.5000
B= 0.2500 INCHES W= 2.3275 INCHES A0= 0.6000 INCHES
TESTING FREQUENCY= 10.0000 HERTZ

TOTAL CYCLES	CRACK LENGTH OBSERVED	CRACK LENGTH CALCULATED	Δ STRESS INTENSITY (KSI-√IN)	GROWTH RATE (IN/CYCLE)
10689.	0.6492			
21500.	0.7000			
32542.	0.7730			
38484.	0.8160	0.8147	70.79	7.892E-06
41836.	0.8410	0.8411	73.08	8.660E-06
49170.	0.9000	0.9057	79.09	1.067E-05
53615.	0.9550	0.9536	83.98	1.316E-05
57141.	1.0000	1.0032	89.48	1.577E-05
59100.	1.0330	1.0345	93.22	1.782E-05
61000.	1.0690	1.0685	97.54	1.966E-05
62500.	1.1000	1.0997	101.78	2.157E-05
65360.	1.1650	1.1662	111.78	2.594E-05
66248.	1.1870	1.1893	115.62	2.979E-05
66617.	1.2000	1.1996	117.38	3.212E-05
67510.	1.2280	1.2264	122.20	3.766E-05
68550.	1.2670	1.2676	130.23	5.177E-05
69250.	1.3000	1.3068	138.64	6.605E-05
69650.	1.3350	1.3331	144.78	8.422E-05
70100.	1.3710	1.3718	154.61	1.130E-04
70423.	1.4000	1.4057	164.13	1.728E-04
70722.	1.4510			
70965.	1.5000			
71155.	1.6000			

TABLE 17
CRACK GROWTH RATE AND STRESS INTENSITY DATA REDUCTION
INCREMENTAL POLYNOMIAL FOR DA/DN

SPECIMEN NUMBER 24-7 APRIL 86

ARC-SHAPED SPECIMEN
LOAD-TO-CRACK DISTANCE =0.0000 INCHES
R1 =2.1635INCHES R2 = 4.4910INCHES

DELTA P= 0.7800 KIPS PMIN= 1.8200 KIPS R= 0.7000
B= 0.2500 INCHES W= 2.3275 INCHES A0= 0.6000 INCHES
TESTING FREQUENCY= 10.0000 HERTZ

TOTAL CYCLES	CRACK LENGTH OBSERVED	CRACK LENGTH CALCULATED	Δ STRESS INTENSITY (KSI-√IN)	GROWTH RATE (IN/CYCLE)
92790.	0.6374			
211200.	0.7000			
278550.	0.7390			
357885.	0.8000	0.7992	12.04	8.021E-07
405570.	0.8370	0.8381	12.62	9.365E-07
440845.	0.8690	0.8721	13.15	1.067E-06
468910.	0.9000	0.9005	13.62	1.223E-06
505635.	0.9470	0.9484	14.46	1.534E-06
522263.	0.9730	0.9717	14.89	1.887E-06
537020.	1.0000	0.9990	15.43	2.114E-06
562285.	1.0510	1.0540	16.58	2.650E-06
602890.	1.1830	1.1853	19.92	4.065E-06
607000.	1.2000	1.2016	20.41	4.463E-06
615600.	1.2390	1.2419	21.69	5.240E-06
620200.	1.2650	1.2637	22.44	5.821E-06
626500.	1.3000	1.3028	23.88	6.799E-06
630000.	1.3280	1.3265	24.82	7.503E-06
634600.	1.3630	1.3629	26.39	8.404E-06
638900.	1.4000	1.3995	28.13	9.815E-06
644100.	1.4540	1.4521	30.98	1.264E-05
648500.	1.5000			
651100.	1.5510			
653100.	1.6000			

TABLE 18

SUMMARY OF VARIABLE AMPLITUDE RESULTS

Specimen	Life to $K_{max}=K_{Ic}=116.3$ ksi$\sqrt{in.}$				(Predicted Life)/(Actual Life)		
Number	Test Data	No Inter-Action	Modified Wheeler	Generalized Willenborg	No Inter-Action	Modified Wheeler	Generalized Willenborg
15	26,056	13,733	25,290	24,014	.527	.971	.922
13*	8,170	8,854	9,807	9,809	1.084	1.200	1.201
9	13,394	12,552	20,360	15,015	.937	1.520	1.121
1*	13,352	13,628	15,429	15,435	1.021	1.156	1.156
22	12,077	12,443	20,205	14,886	1.030	1.673	1.233
30	25,000	16,082	18,694	16,926	.643	.748	.678
10	25,622	22,445	23,648	22,837	.876	.923	.891
26	2,360	2,597	3,477	2,898	1.100	1.473	1.228
7	5,571	4,996	6,384	6,215	.897	1.146	1.116
28*	8.742	11,081	11,626	11,631	1.268	1.330	1.330
29	6,068	4,963	6,343	6,175	.818	1.045	1.018
17	3,404	3,919	5,142	4,342	1.151	1.511	1.276
				Mean	.946	1.225	1.098
				Std. Dev.	.212	.281	.189

*Compressive loads

TABLE 19
VARIABLE AMPLITUDE TEST DATA
SPECIMEN NUMBER 15
LOAD HISTORY A FORWARD

CRACK LENGTH (INCHES)	NUMBER BLOCKS
.6315	2679
.665	5131
.700	7560
.739	10090
.775	11631
.800	13820
.855	16216
.900	18268
.962	20332
1.000	21372
1.047	22480
1.100	23435
1.135	23992
1.163	24393
1.200	24776
1.237	25077
1.275	25397
1.300	25551
1.341	25749
1.369	25855
1.400	25964
1.433	26044
1.475	26099
1.500	26151

TABLE 20
VARIABLE AMPLITUDE TEST DATA
SPECIMEN NUMBER 13
LOAD HISTORY A FORWARD

CRACK LENGTH (INCHES)	NUMBER BLOCKS
.6433	1000
.6689	1628
.700	2306
.733	3042
.769	3765
.800	4271
.833	4798
.900	5613
.957	6287
1.000	6716
1.033	7009
1.071	7322
1.12	7660
1.159	7822
1.200	7967
1.247	8118
1.285	8194
1.300	8240
1.337	8284
1.371	8323
1.400	8353
1.463	8392
1.500	8402

TABLE 21
VARIABLE AMPLITUDE TEST DATA
SPECIMEN NUMBER 9
LOAD HISTORY A FORWARD

CRACK LENGTH (INCHES)	NUMBER BLOCKS
.6354	1800
.700	4200
.757	5879
.800	6989
.867	8460
.900	9145
.971	10233
1.00	10650
1.033	11072
1.075	11543
1.100	11794
1.133	12110
1.169	12375
1.200	12632
1.247	12905
1.300	13169
1.341	13345
1.400	13536
1.443	13644
1.500	13775

TABLE 22
VARIABLE AMPLITUDE TEST DATA
SPECIMEN NUMBER 1
LOAD HISTORY A BACKWARD

CRACK LENGTH (INCHES)	NUMBER BLOCKS
.6315	1409
.665	2692
.700	3775
.743	5285
.800	7250
.843	8038
.900	9265
.924	10370
1.020	11195
1.051	11560
1.100	12008
1.149	12315
1.167	12645
1.200	12793
1.231	12980
1.275	13118
1.300	13211
1.377	13405
1.400	13427
1.426	13458
1.459	13486
1.500	13505

TABLE 23
VARIABLE AMPLITUDE TEST DATA
SPECIMEN NUMBER 22
LOAD HISTORY A BACKWARD

CRACK LENGTH (INCHES)	NUMBER BLOCKS
.6453	1908
.700	3713
.732	4701
.767	5575
.800	6288
.833	7015
.865	7638
.900	8215
.933	8776
.977	9375
1.000	9618
1.035	10038
1.065	10340
1.100	10643
1.133	10917
1.161	11126
1.200	11389
1.235	11578
1.269	11751
1.300	11865
1.333	12005
1.365	12125
1.400	12209
1.433	12302
1.475	12383
1.500	12412
1.528	12436

TABLE 24
VARIABLE AMPLITUDE TEST DATA
SPECIMEN NUMBER 30
LOAD HISTORY A BACKWARD

CRACK LENGTH	NUMBER BLOCKS
(INCHES)	
.6335	3167
.6768	6445
.728	9575
.759	11300
.800	13325
.851	15683
.900	17425
.961	19475
1.000	20440
1.059	21850
1.100	22708
1.135	23289
1.173	23882
1.200	24160
1.235	24600
1.267	24964
1.300	25259
1.333	25534
1.365	25737
1.400	25897
1.428	26052
1.461	26143
1.500	26195

TABLE 25
VARIABLE AMPLITUDE TEST DATA
SPECIMEN NUMBER 10
LOAD HISTORY B FORWARD

CRACK LENGTH	NUMBER BLOCKS
(INCHES)	
.6335	3171
.663	5702
.700	8068
.735	10666
.777	12939
.824	15168
.877	17311
.900	18095
.945	19383
1.000	20674
1.049	21710
1.100	22671
1.169	23539
1.200	23892
1.245	24327
1.300	24769
1.335	25030
1.371	25264
1.400	25399
1.439	25611
1.500	25824

TABLE 26
VARIABLE AMPLITUDE TEST DATA
SPECIMEN NUMBER 26
LOAD HISTORY B FORWARD

CRACK LENGTH (INCHES)	NUMBER BLOCKS
.6492	352
.700	675
.735	880
.800	1213
.861	1506
.900	1671
.935	1789
.977	1910
1.000	1962
1.033	2060
1.073	2151
1.100	2205
1.135	2278
1.177	2326
1.200	2371
1.255	2436
1.300	2472
1.32	2491
1.373	2511
1.400	2518

TABLE 27
VARIABLE AMPLITUDE TEST DATA
SPECIMEN NUMBER 7
LOAD HISTORY B FORWARD

CRACK LENGTH (INCHES)	NUMBER BLOCKS
.6807	1403
.700	1678
.733	2180
.773	2678
.800	2991
.845	3487
.871	3700
.900	3911
.933	4159
.975	4406
1.000	4515
1.037	4720
1.071	4860
1.100	4980
1.137	5100
1.173	5205
1.200	5274
1.233	5359
1.271	5418
1.300	5462
1.335	5501
1.400	5542
1.455	5579

TABLE 28
VARIABLE AMPLITUDE TEST DATA
SPECIMEN NUMBER 28
LOAD HISTORY B BACKWARD

CRACK LENGTH (INCHES)	NUMBER BLOCKS
.6413	1210
.700	2525
.747	3696
.800	4621
.849	5310
.900	5931
.949	6451
1.000	6903
1.069	7443
1.100	7614
1.147	7889
1.171	7995
1.200	8104
1.255	8296
1.273	8359
1.300	8439
1.333	8514
1.375	8591
1.400	8625
1.431	8663
1.465	8698
1.500	8729
1.535	8742
1.600	8761

TABLE 29
VARIABLE AMPLITUDE TEST DATA
SPECIMEN NUMBER 29
LOAD HISTORY B BACKWARD

CRACK LENGTH	NUMBER BLOCKS
(INCHES)	
.635	691
.716	2156
.769	2910
.800	3279
.833	3660
.900	4296
.937	4542
1.000	4954
1.033	5120
1.067	5303
1.100	5420
1.133	5543
1.167	5657
1.200	5742
1.233	5808
1.267	5873
1.300	5930
1.331	5974
1.367	6023
1.400	6045
1.433	6064
1.464	6080
1.500	6090
1.531	6099

TABLE 30
VARIABLE AMPLITUDE TEST DATA
SPECIMEN NUMBER 17
LOAD HISTORY B BACKWARD

CRACK LENGTH (INCHES)	NUMBER BLOCKS
.6394	514
.700	1063
.755	1482
.82	1915
.869	2196
.900	2368
.947	2577
1.000	2784
1.043	2925
1.100	3087
1.149	3194
1.200	3296
1.253	3379
1.300	3436
1.326	3495
1.353	3465
1.400	3514
1.449	3539

X. APPENDICES

```
C***********************************************************************
C                          ------CRACK------                           *
C     THIS PROGRAM CALCULATES THE EXPECTED LIFE OF AN ARC-SHAPED       *
C     SPECIMEN WITH AN INITIAL CRACK LENGTH.  SEE INPUT SUBROUTINE FOR *
C     EXPLANATION OF VARIABLES. THREE DIFFERENT PREDICTIONS CAN BE     *
C     MADE WITH THIS PROGRAM--ICODE=1 WILL USE A MODIFIED WHEELER MODEL*
C     ICODE=2 WILL USE A GENERALIZED WILLENBORG MODEL AND ICODE=3 WILL *
C     RUN THE NO-INTERACTION CASE USING THE WALKER EQUATION.           *
C     ALL INPUT IS FREE FORMAT AND CONVENTIONAL VARIABLE SPECIFICATION *
C     IS USED WITH THE EXCEPTION THAT ALL VARIABLES BEGINNING WITH "K" *
C     HAVE BEEN DECLARED AS REAL VARIABLES.                            *
C***********************************************************************
      IMPLICIT REAL*4 (K)
      COMMON/DATA1/SY,WALKC,WALKM,WALKN,WHEELM,KIC
      COMMON/DATA2/ROL,AOL,ASUM
      COMMON/SIF/KMIN, KMAX, DELTK,DADN
      COMMON/DIMEN/W,B,X,R1,R2,A0
      COMMON/LOAD/NREPS,NBLKS,NCYCLS(500),PMAX(50),PMIN(50),R(50)
      COMMON/MODEL/ICODE,S,DKTH
C*****
C     READ IN MATERIAL AND LOAD HISTORY DATA
C*****
      CALL IN
      PI=ARCOS(-1.)
C*****
C     INITIALIZE CURRENT CRACK LENGTH, AI, & OVERLOAD CRACK LENGTH, AOL
C*****
    5 AI=A0
      AOL=A0
      ROL=0.
      ASUM=0.
C*****
C     ESTABLISH PRINT CONTROL VARIABLE
C*****
      PRINT=A0
C*****
C     FIND MAXIMUM LOAD IN REPEATED HISTORY
C*****
      P=0.
      DO 10 I=1,NBLKS
   10 IF(PMAX(I).GT.P)P=PMAX(I)
C*****
C     FIND CRITICAL CRACK LENGTH FOR FULLY PLASTIC YIELDING
C*****
      Q=P/(1.26*SY*B*(W+X))
      ACRIT=(W+X)*(Q+1.-SQRT(Q*(Q+4.)))
C*****
C     PRINT INPUT DATA AND COLUMN HEADINGS
C*****
      CALL HEADER(ACRIT)
C*****
```

```
C     INITIALIZE CYCLE COUNTER
C*****
      I=0
      DO 100 IREP=1,NREPS
           DO 100 IBLK=1,NBLKS
                NC=NCYCLS(IBLK)
                DO 90 ICYCL=1,NC
                I=I+1
C*****
C     SET MAXIMUM LIMIT ON CYCLES IN CASE OF ERROR
C*****
                IF(I.GT.4.E06)GO TO 999
C*****
C     CALCULATE STRESS INTENSITY FACTOR RANGE FOR EACH CYCLE
C*****
               CALL STRESS(AI,KIC,I,IBLK)
C*****
C     CHECK FAILURE CONDITIONS FOR BRITTLE FRACTURE OR YIELDING
C*****
               CALL FAIL(IREP,KMAX,ACRIT,AI,KIC,I,SY,IFLAG)
C*****
C     CHECK FAILURE FLAG
C*****
               IF(IFLAG.GT.0)GO TO 998
C*****
C     CALCULATE NEW CRACK DATA
C*****
               IF(ICODE.EQ.1.OR.ICODE.EQ.3)THEN
               CALL WHEEL(AI,AO,IBLK,CI,RYI,PI)
               ELSE
               CALL WILBRG(AI,AO,IBLK,CI,RYI,PI)
               END IF
C*****
C     CALCULATE OVERLOAD (ZOL) AND CURRENT (ZYI) AFFECTED ZONES
C*****
               ZYI=RYI+AI
               ZOL=ROL+AOL
C*****
C     PRINT CONTROL IS OPTIONAL--THIS PRINTS OUT FIRST BLOCK DATA
C     AND DATA WHEN CRACK GROWS 0.1 INCHES
C*****
      IF(IREP.EQ.1)WRITE(6,1002)IREP,I,CI,DYI,DOL,AI,DELTK,DADN
      IF(AI.GE.(PRINT+.1))THEN
      PRINT=PRINT+.1
      WRITE(6,1002)IREP,I,CI,ZYI,ZOL,AI,DELTK,DADN
      ELSE
      END IF
   90 CONTINUE
  100 CONTINUE
C*****
C     IF PROGRAM RUNS OUT OF CYCLES WITHOUT FAILURE--ERROR MESSAGE
C*****
```

```
      WRITE(6,1003)I,AI
C*****
C     IF ALL THREE MODELS ARE DESIRED (NO-INTERACTION, WHEELER, AND
C     WILLENBORG, THEN PUT AN INCREMENT ON ICODE AT 998 AND LOOP THE
C     PROGRAM BACK TO 5 UNTIL ICODE IS GREATER THAN 3
C*****
  998 CONTINUE
  999 STOP
 1002 FORMAT(1X,2I8,6E15.7)
 1003 FORMAT(T5,'MAX NUMBER OF CYCLES(',I8,') EXCEEDED WITHOUT FAILURE.'
     1/T5,'CRACK LENGTH =',E15.7)
      END
*********************************************************************************
      SUBROUTINE IN
C*****
C     SY=YIELD STRENGTH;  WALKC=C CONSTANT IN WALKER EQUATION;  WALKM,
C     WALKN=M,N EXPONENTS IN WALKER EQUATION;  WHEELM=M EXPONENT IN
C     WHEELER MODEL;  KIC=MATERIAL FRACTURE TOUGHNESS
C
C     W=WIDTH OF SPECIMEN;  B=THICKNESS OF SPECIMEN;  X=DISTANCE FROM
C     POINT LOAD IS APPLIED TO CRACK TIP;  R1,R2=INNER AND OUTER RADII;
C     A0=INITIAL CRACK LENGTH
C
C     NREPS=# OF REPEATED LOADING SEQUENCES;NBLKS=# OF DIFFERENT LOADING
C     RATIOS(R) IN EACH SEQUENCE;  NCYCLS=# OF INDIVIDUAL CYCLES OF EACH
C     R-VALUE;  PMAX,PMIN=MAX AND MIN LOADS FOR EACH R VALUE;
C     R=RATIO OF PMIN TO PMAX
C
C     ROL=PLASTIC ZONE CAUSED BY OVERLOAD;  AOL=CRACK LENGTH AT
C     OVERLOAD;  ASUM=SUMMED CRACK GROWTH
C     DKTH IS THE THRESHOLD DELTA K FOR THE MATERIAL
C     S IS THE OVERLOAD SHUTOFF RATIO AS DEFINED BY GALLAGHER
*****
C     THIS SUBROUTINE INITIALIZES ALL MATERIAL CONSTANTS AND PARAMETERS
C     FOR JOB PROCESSING WITH INPUT FROM A DATA FILE
C*****
      IMPLICIT REAL*4 (K)
      COMMON/DATA1/SY,WALKC,WALKM,WALKN,WHEELM,KIC
      COMMON/DATA2/ROL,AOL,ASUM
      COMMON/DIMEN/W,B,X,R1,R2,A0
      COMMON/LOAD/NREPS,NBLKS,NCYCLS(500),PMAX(50),PMIN(50),R(50)
      COMMON/MODEL/ICODE,S,DKTH
C*****
C     ICODE DETERMINES WHETHER TO USE WHEELER OR WILLENBORG MODELS
C     OR THE NO-INTERACTION MODEL
C*****
      READ(5,*)ICODE
      READ(5,*)S
      READ(5,*)DKTH
      READ(5,*)SY
      READ(5,*)WALKC
      READ(5,*)WALKM
```

```
      READ(5,*)WALKN
      READ(5,*)KIC
      READ(5,*)B
      READ(5,*)X
      READ(5,*)R1
      READ(5,*)R2
      READ(5,*)A0
      READ(5,*)NREPS
      READ(5,*)NBLKS
      DO 300 I=1,NBLKS
      READ(5,*)NCYCLS(I)
      READ(5,*)PMIN(I)
C*********WARNING*********WARNING********WARNING********WARNING**************
C     IF THE MAXIMUM LOAD IN A CYCLE IS ZERO, A SMALL NUMBER MUST BE
C     INPUT TO AVOID A DIVISION BY ZERO ERROR
C*********WARNING*********WARNING********WARNING********WARNING**************
      READ(5,*)PMAX(I)
  300 R(I)=PMIN(I)/PMAX(I)
      W=R2-R1
      RETURN
      END
****************************************************************************
      SUBROUTINE HEADER(ACRIT)
C*****
C     THIS SUBROUTINE WRITES OUT ALL THE INPUT DATA AND THE HEADINGS FOR
C     THE OUTPUT.
C*****
      IMPLICIT REAL*4 (K)
      COMMON/DATA1/SY,WALKC,WALKM,WALKN,WHEELM,KIC
      COMMON/DIMEN/W,B,X,R1,R2,A0
      COMMON/LOAD/NREPS,NBLKS,NCYCLS(500),PMAX(50),PMIN(50),R(50)
      COMMON/MODEL/ICODE,S,DKTH
      WRITE(6,1004)W,R1,R2,X,A0,B
      WRITE(6,1005)SY,KIC,WALKC,WALKM,WALKN
      WRITE(6,1006)
      WRITE(6,1007)NREPS,(R(I),NCYCLS(I),PMIN(I),PMAX(I),I=1,NBLKS)
      GO TO (10,20,30),ICODE
   10 WRITE(6,1002)
      GO TO 40
   20 WRITE(6,1003)
      GO TO 40
   30 WRITE(6,1008)
   40 WRITE(6,1009)ACRIT
      IF(ICODE.EQ.1.OR.ICODE.EQ.3)THEN
      WRITE(6,1000)
      ELSE
      WRITE(6,1001)
      END IF
 1000 FORMAT(1H1,T4,'REP#',T11,'CYCLE#',T24,'CI',T37,'RYI+AI',T52,'ROL+A
     1OL',T70,'A',T82,'DELTA K',T98,'DA/DN'/'+',107('_'))
 1001 FORMAT(1H1,T4,'REP#',T11,'CYCLE#',T24,'PHI',T37,'RYI+AI',T52,'ROL+
     1AOL',T70,'A',T82,'DELTA K',T98,'DA/DN'/'+',107('_'))
```

```
 1002 FORMAT(///5X,'USES THE WHEELER MODEL TO ACCOUNT FOR RETARDATION
     *OF CRACK GROWTH'//)
 1003 FORMAT(///5X,'USES THE WILLENBORG MODEL TO ACCOUNT'/
     *5X,'FOR RETARDATION OF CRACK GROWTH'//)
 1004 FORMAT(1H1,T5,'C-SHAPED SPECIMEN DIMENSIONS'/'+',T5,27('_')//T5,'W
     1IDTH =',E12.5,' INCHES'/T5,'INNER RADIUS =',E12.5,' INCHES'/T5,'OU
     2TER RADIUS =',E12.5,' INCHES'/T5,'LOAD-TO-CRACK DISTANCE =',E12.5,
     3' INCHES'/T5,'INITIAL CRACK LENGTH =',E12.5,'INCHES'/T5,'SPECIMEN
     4THICKNESS =',E12.5,' INCHES'//)
 1005 FORMAT(T5,'MATERIAL PROPERTIES'/'+',T5,19('_')//T5,'YIELD STRENGTH
     1 =',E12.5,' KSI'/T5,'FRACTURE TOUGHNESS =',E12.5,' KSI-(IN)1/2'/T5
     2,'C-COEFFICIENT IN WALKER EQN =',E12.5/T5,'M-EXPONENT IN WALKER EQ
     3N =',E12.5/T5,'N-EXPONENT IN WALKER EQN =',E12.5//)
 1006 FORMAT(T5,'LOAD PARAMETERS'/'+',T5,15('_')//)
 1007 FORMAT(T5,'MAX NO. OF REPEATED SEQUENCES=',I6//T13,'R',T23,'# OF C
     1YCLES',2X,'MIN LOAD (KSI)',2X,'MAX LOAD (KSI)'/'+',T5,60('_')//(T5
     2,E15.7,I7,8X,2E15.7))
 1008 FORMAT(///5X,'USES WALKER EQUATION AND DOES NOT ACCOUNT FOR INTERA
     *CTION EFFECTS'//)
 1009 FORMAT(//5X,'CRITICAL CRACK LENGTH FOR TOTAL YIELDING = ',F10.5//)
      RETURN
      END
************************************************************************
      SUBROUTINE STRESS(AI,KIC,I,IK)
C*****
C     CALCULATES THE CURRENT STRESS INTENSITY FACTOR MIN, MAX AND DELTA
C     K ONLY FOR AN ARC-SHAPED SPECIMEN
C*****
      IMPLICIT REAL*4 (K)
      COMMON/DIMEN/W,B,X,R1,R2,A0
      COMMON/LOAD/NREPS,NBLKS,NCYCLS(500),PMAX(50),PMIN(50),R(50)
      COMMON/SIF/KMIN, KMAX, DELTK,DADN
      AW=AI/W
      FAW=(SQRT(AW)/(1.-AW)**1.5)*(3.74-6.3*AW+6.32*AW*AW-2.43*AW**3)
      FCT=(3*X/W+1.9+1.1*AW)*(1.+.25*(1.-AW)**2*(1.-R1/R2))/(B*SQRT(W))
      KMIN=PMIN(IK)*FCT*FAW
      KMAX=PMAX(IK)*FCT*FAW
      DELTK=KMAX-KMIN
      RETURN
      END
************************************************************************
      SUBROUTINE FAIL(IREP,KMAX,ACRIT,AI,KIC,I,SY,IFLAG)
C*****
C     CALCULATES FAILURE BY PLASTIC YIELDING OR BRITTLE FRACTURE
C*****
      IMPLICIT REAL*4 (K)
      COMMON/DIMEN/W,B,X,R1,R2,A0
      IFLAG=0
      APRIM=X+AI
      WPRIM=X+W
      AWP=APRIM/WPRIM
C*****
```

```
C     CHECK TO SEE IF FAILURE HAS OCCURRED
C*****
      IF((KMAX.GE.KIC).AND.(APRIM.GE.ACRIT))THEN
      WRITE(6,1201)I,IREP
      IFLAG=1
      ELSE
      IF(KMAX.GE.KIC)THEN
      WRITE(6,1202)I,IREP,KMAX,AI
      IFLAG=1
      ELSE
      IF(APRIM.GE.ACRIT)THEN
      WRITE(6,1203)I,IREP,ACRIT,AI
      IFLAG=1
      ELSE
      END IF
      END IF
      END IF
 1201 FORMAT(/T5,'BOTH FRACTURE TOUGHNESS AND PLASTIC YIELD LIMITS ARE',
     1/T5,'EXCEEDED ON CYCLE NUMBER ',I8,' BLOCK NUMBER ',I8/)
 1202 FORMAT(/T5,'FAILURE OCCURRED ON CYCLE NUMBER ',I8,' BLOCK NUMBER '
     1,I8,/T5,'DUE TO BRITTLE FRACTURE.'/T5,' KMAX = ',E15.7,2X,
     2' CRACK LENGTH = ',E15.7/)
 1203 FORMAT(/T5,'FAILURE OCCURRED ON CYCLE NUMBER',I8,' BLOCK NUMBER '
     1,I8,/T5,' DUE TO TOTAL PLASTIC YIELDING.'/T5,' ACRIT = ',E15.7,
     22X,' CRACK LENGTH = ',E15.7/)
      RETURN
      END
***********************************************************************
      SUBROUTINE WHEEL(AI,A0,IK,CI,RYI,PI)
C*****
C     CALCULATES THE PLASTIC ZONE, OVERLOAD ZONE AND CRACK GROWTH USING
C     MODIFIED WHEELER MODEL WITH WALKER CRACK GROWTH EQUATION
C*****
      IMPLICIT REAL*4 (K)
      COMMON/DATA1/SY,WALKC,WALKM,WALKN,WHEELM,KIC
      COMMON/DATA2/ROL,AOL,ASUM
      COMMON/SIF/KMIN, KMAX, DELTK,DADN
      COMMON/LOAD/NREPS,NBLKS,NCYCLS(500),PMAX(50),PMIN(50),R(50)
      COMMON/MODEL/ICODE,S,DKTH
      DK=DELTK
C*****
C     MUST IGNORE COMPRESSION EFFECTS IN THIS MODEL
C*****
      IF(R(IK).LT.0.01)DK=KMAX
      IF(PMAX(IK).LT.0.01) THEN
      RYI=0.
      DADN=0.
      CI=0.
      RETURN
      END IF
      WHEELM=WALKN/2.0*(ALOG10(DK/DKTH)/ALOG10(S))
C*****
```

```
C     IF NO INTERACTION CASE IS BEING RUN, SET WHEELM TO ZERO
C*****
      IF(ICODE.EQ.3)WHEELM=0.
C*****
C     CALCULATE INSTANTANEOUS YIELD ZONE
C*****
      RYI=.5/PI*(KMAX/SY)**2
C*****
C     CHECK TO SEE IF CRACK HAS GROWN OUT OF OVERLOAD ZONE
C*****
      IF((RYI+AI).GE.(AOL+ROL))THEN
      ROL=RYI
      AOL=AI
      CI=1.0
      ELSE
      CI=(RYI/(AOL+ROL-AI))**WHEELM
      END IF
C*****
C     IF DELTA K IS BELOW THE THRESHOLD DELTA K, NO GROWTH OCCURS
C*****
      IF(DK.LT.DKTH)CI=0.
C*****
C     CALCULATE CRACK GROWTH
C*****
      XM=WALKM
C*****
C     TO IGNORE COMPRESSIVE LOADS, SET WALKM EQUAL TO ZERO
C*****
      IF(R(IK).LT.0.01)XM=0.
      DADN=WALKC*(DELTK/(1.-R(IK))**(1.-XM))**WALKN
      ASUM=ASUM+CI*DADN
      AI=A0+ASUM
      RETURN
      END
***************************************************************************
      SUBROUTINE WILBRG(AI,A0,IK,PHI,RYI,PI)
C*****
C     THIS SUBROUTINE CALCULATES CRACK GROWTH BASED ON THE GENERALIZED
C     WILLENBORG MODEL.  COMPRESSIVE LOADS ARE IGNORED.
C*****
      IMPLICIT REAL*4 (K)
      COMMON/DATA1/SY,WALKC,WALKM,WALKN,WHEELM,KIC
      COMMON/DATA2/ROL,AOL,ASUM
      COMMON/SIF/KMIN, KMAX, DELTK,DADN
      COMMON/LOAD/NREPS,NBLKS,NCYCLS(500),PMAX(50),PMIN(50),R(50)
      COMMON/MODEL/ICODE,S,DKTH
C*****
C     CALCULATE INSTANTANEOUS YIELD ZONE
C*****
      RYI=.5/PI*(KMAX/SY)**2
C*****
```

```
C     CHECK TO SEE IF CRACK HAS GROWN OUT OF OVERLOAD ZONE
C*****
      IF((RYI+AI).GE.(AOL+ROL))THEN
      ROL=RYI
      AOL=AI
      KOL=KMAX
      ELSE
      END IF
C*****
C     NO GROWTH OCCURS IF THERE IS NO POSITIVE TENSILE LOAD
C     IF DELTA K IS BELOW THE THRESHOLD DELTA K, NO GROWTH OCCURS
C*****
      IF((PMAX(IK).LT.0.01).OR.(DELTK.LT.DKTH)) THEN
      RYI=0.
      PHI=0.
      DADN=0.
      RETURN
      ELSE
      END IF
C*****
C     CALCULATE KMAX THRESHOLD
C*****
      KMAXTH=DKTH/(1.-R(IK))
      IF(R(IK).LT.0.)KMAXTH=DKTH
C*****
C     CALCULATE CRACK GROWTH SINCE OVERLOAD
C*****
      DELA=AI-AOL
C*****
C     CALCULATE RETARDATION PARAMETER AND EFFECTIVE STRESS INTENSITIES
C*****
      PHI=(1.-KMAXTH/KMAX)/(S-1.)
      KRED=KOL*SQRT(1.-DELA/ROL)-KMAX
      KMAXEF=KMAX-PHI*KRED
      KMINEF=KMIN-PHI*KRED
      DKEFF=KMAXEF-KMINEF
C*****
C     PREVENT UNDERFLOW DIVIDE ERROR
C*****
      IF(KMAXEF.LT.1.0E-09)THEN
      DADN=0.
      RETURN
      ELSE
      REFF=KMINEF/KMAXEF
      END IF
C
C     CALCULATE CRACK GROWTH
C
      XM=WALKM
      IF(REFF.LT.0.)XM=0.
      DADN=WALKC*(DKEFF/(1.-REFF)**(1.-XM))**WALKN
      ASUM=ASUM+DADN
```

```
AI=AO+ASUM
RETURN
END
```

****THIS IS SAMPLE INPUT DATA FOR PROGRAM CRACK FOR SPEC. #15****

```
1
2.3
6.
182.05
2.732E-11
.420
3.2423
116.3
.25
0.0
2.16
4.491
.600
100000
4
3
0.00
3.
6
0.00
1.85
12
0.0
1.35
24
0.00
1.00
```

THIS IS AN EXAMPLE OUTPUT FOR PROGRAM CRACK USING SPEC. #15 DATA.

C-SHAPED SPECIMEN DIMENSIONS

WIDTH = 0.23310E+01 INCHES
INNER RADIUS = 0.21600E+01 INCHES
OUTER RADIUS = 0.44910E+01 INCHES
LOAD-TO-CRACK DISTANCE = 0.00000E+00 INCHES
INITIAL CRACK LENGTH = 0.60000E+00INCHES
SPECIMEN THICKNESS = 0.25000E+00 INCHES

MATERIAL PROPERTIES

YIELD STRENGTH = 0.18205E+03 KSI
FRACTURE TOUGHNESS = 0.11630E+03 KSI-(IN)1/2
C-COEFFICIENT IN WALKER EQN = 0.27320E-10
M-EXPONENT IN WALKER EQN = 0.42000E+00
N-EXPONENT IN WALKER EQN = 0.32423E+01

LOAD PARAMETERS

MAX NO. OF REPEATED SEQUENCES=100000

R	# OF CYCLES	MIN LOAD (KSI)	MAX LOAD (KSI)
0.0000000E+00	3	0.0000000E+00	0.3000000E+01
0.0000000E+00	6	0.0000000E+00	0.1800000E+01
0.0000000E+00	12	0.0000000E+00	0.1350000E+01
0.0000000E+00	24	0.0000000E+00	0.1000000E+01

USES THE WHEELER MODEL TO ACCOUNT FOR RETARDATION OF CRACK GROWTH

CRITICAL CRACK LENGTH FOR TOTAL YIELDING = 1.68295

REP#	CYCLE#	CI	A	DELTA K	DA/DN
1	1	0.1000000E+01	0.6000031E+00	0.3638020E+02	0.3142483E-05
1	2	0.1000000E+01	0.6000063E+00	0.3638034E+02	0.3142522E-05
1	3	0.1000000E+01	0.6000094E+00	0.3638045E+02	0.3142553E-05
1	4	0.7678264E-01	0.6000094E+00	0.2182835E+02	0.5997753E-06
1	5	0.7678264E-01	0.6000095E+00	0.2182835E+02	0.5997753E-06
1	6	0.7678449E-01	0.6000096E+00	0.2182835E+02	0.5997753E-06
1	7	0.7678634E-01	0.6000096E+00	0.2182835E+02	0.5997753E-06
1	8	0.7678819E-01	0.6000097E+00	0.2182835E+02	0.5997753E-06
1	9	0.7678986E-01	0.6000097E+00	0.2182835E+02	0.5997753E-06
1	10	0.4420032E-01	0.6000097E+00	0.1637128E+02	0.2359935E-06
1	11	0.4420032E-01	0.6000097E+00	0.1637128E+02	0.2359935E-06
1	12	0.4420141E-01	0.6000097E+00	0.1637129E+02	0.2359944E-06
1	13	0.4420141E-01	0.6000097E+00	0.1637129E+02	0.2359944E-06
1	14	0.4420141E-01	0.6000097E+00	0.1637129E+02	0.2359944E-06
1	15	0.4420141E-01	0.6000097E+00	0.1637129E+02	0.2359944E-06
1	16	0.4420141E-01	0.6000098E+00	0.1637129E+02	0.2359944E-06
1	17	0.4420221E-01	0.6000098E+00	0.1637129E+02	0.2359944E-06
1	18	0.4420221E-01	0.6000098E+00	0.1637129E+02	0.2359944E-06
1	19	0.4420221E-01	0.6000098E+00	0.1637129E+02	0.2359944E-06
1	20	0.4420221E-01	0.6000098E+00	0.1637129E+02	0.2359944E-06
1	21	0.4420221E-01	0.6000098E+00	0.1637129E+02	0.2359944E-06
1	22	0.4936459E-01	0.6000098E+00	0.1212688E+02	0.8919073E-07
1	23	0.4936459E-01	0.6000099E+00	0.1212688E+02	0.8919073E-07
1	24	0.4936515E-01	0.6000099E+00	0.1212689E+02	0.8919096E-07
1	25	0.4936515E-01	0.6000099E+00	0.1212689E+02	0.8919096E-07
1	26	0.4936515E-01	0.6000099E+00	0.1212689E+02	0.8919096E-07
1	27	0.4936515E-01	0.6000099E+00	0.1212689E+02	0.8919096E-07
1	28	0.4936515E-01	0.6000099E+00	0.1212689E+02	0.8919096E-07
1	29	0.4936515E-01	0.6000099E+00	0.1212689E+02	0.8919096E-07
1	30	0.4936515E-01	0.6000099E+00	0.1212689E+02	0.8919096E-07
1	31	0.4936515E-01	0.6000099E+00	0.1212689E+02	0.8919096E-07
1	32	0.4936515E-01	0.6000099E+00	0.1212689E+02	0.8919096E-07
1	33	0.4936515E-01	0.6000099E+00	0.1212689E+02	0.8919096E-07
1	34	0.4936515E-01	0.6000099E+00	0.1212689E+02	0.8919096E-07
1	35	0.4936515E-01	0.6000099E+00	0.1212689E+02	0.8919096E-07
1	36	0.4936515E-01	0.6000099E+00	0.1212689E+02	0.8919096E-07
1	37	0.4936576E-01	0.6000099E+00	0.1212689E+02	0.8919096E-07
1	38	0.4936576E-01	0.6000099E+00	0.1212689E+02	0.8919096E-07
1	39	0.4936576E-01	0.6000099E+00	0.1212689E+02	0.8919096E-07
1	40	0.4936576E-01	0.6000099E+00	0.1212689E+02	0.8919096E-07
1	41	0.4936576E-01	0.6000099E+00	0.1212689E+02	0.8919096E-07
1	42	0.4936576E-01	0.6000099E+00	0.1212689E+02	0.8919096E-07
1	43	0.4936576E-01	0.6000099E+00	0.1212689E+02	0.8919096E-07
1	44	0.4936576E-01	0.6000099E+00	0.1212689E+02	0.8919096E-07
1	45	0.4936576E-01	0.6000099E+00	0.1212689E+02	0.8919096E-07
8544	384438	0.1000000E+01	0.7000030E+00	0.4105991E+02	0.4652270E-05
14490	652006	0.1000000E+01	0.8000007E+00	0.4626845E+02	0.6852260E-05
18472	831196	0.1000000E+01	0.9000026E+00	0.5223531E+02	0.1015395E-04
21152	951796	0.1000000E+01	0.1000014E+01	0.5924681E+02	0.1527536E-04
22919	1031313	0.1000000E+01	0.1100001E+01	0.6767502E+02	0.2351138E-04

24054	1082388	0.1000000E+01	0.1200009E+01	0.7803577E+02	0.3731334E-04
24757	1114021	0.1000000E+01	0.1300041E+01	0.9105888E+02	0.6154472E-04
25174	1132788	0.1000000E+01	0.1400053E+01	0.1078132E+03	0.1064174E-03

FAILURE OCCURRED ON CYCLE NUMBER 1138008 BLOCK NUMBER 25290
DUE TO BRITTLE FRACTURE.
KMAX = 0.1163024E+03 CRACK LENGTH = 0.1441780E+01

C-SHAPED SPECIMEN DIMENSIONS

WIDTH = 0.23310E+01 INCHES
INNER RADIUS = 0.21600E+01 INCHES
OUTER RADIUS = 0.44910E+01 INCHES
LOAD-TO-CRACK DISTANCE = 0.00000E+00 INCHES
INITIAL CRACK LENGTH = 0.60000E+00INCHES
SPECIMEN THICKNESS = 0.25000E+00 INCHES

MATERIAL PROPERTIES

YIELD STRENGTH = 0.18205E+03 KSI
FRACTURE TOUGHNESS = 0.11630E+03 KSI-(IN)1/2
C-COEFFICIENT IN WALKER EQN = 0.27320E-10
M-EXPONENT IN WALKER EQN = 0.42000E+00
N-EXPONENT IN WALKER EQN = 0.32423E+01

LOAD PARAMETERS

MAX NO. OF REPEATED SEQUENCES=100000

R	# OF CYCLES	MIN LOAD (KSI)	MAX LOAD (KSI)
0.0000000E+00	3	0.0000000E+00	0.3000000E+01
0.0000000E+00	6	0.0000000E+00	0.1800000E+01
0.0000000E+00	12	0.0000000E+00	0.1350000E+01
0.0000000E+00	24	0.0000000E+00	0.1000000E+01

USES THE WILLENBORG MODEL TO ACCOUNT
FOR RETARDATION OF CRACK GROWTH

CRITICAL CRACK LENGTH FOR TOTAL YIELDING = 1.68295

REP#	CYCLE#	PHI	A	DELTA K	DA/DN
1	1	0.6423654E+00	0.6000031E+00	0.3638020E+02	0.3142483E-05
8122	365447	0.6568245E+00	0.7000018E+00	0.4105988E+02	0.4652270E-05
13722	617448	0.6694788E+00	0.8000050E+00	0.4626868E+02	0.6852364E-05
17522	788447	0.6808738E+00	0.9000093E+00	0.5223573E+02	0.1015423E-04
20074	903286	0.6913289E+00	0.1000006E+01	0.5924626E+02	0.1527490E-04
21755	978931	0.7010313E+00	0.1100001E+01	0.6767490E+02	0.2351122E-04
22834	1027488	0.7100871E+00	0.1200020E+01	0.7803700E+02	0.3731530E-04
23504	1057638	0.7185449E+00	0.1300041E+01	0.9105882E+02	0.6154472E-04
23903	1075592	0.7264248E+00	0.1400094E+01	0.1078212E+03	0.1064426E-03

FAILURE OCCURRED ON CYCLE NUMBER 1080587 BLOCK NUMBER 24014
DUE TO BRITTLE FRACTURE.
KMAX = 0.1163276E+03 CRACK LENGTH = 0.1441897E+01

C-SHAPED SPECIMEN DIMENSIONS

WIDTH = 0.23310E+01 INCHES
INNER RADIUS = 0.21600E+01 INCHES
OUTER RADIUS = 0.44910E+01 INCHES
LOAD-TO-CRACK DISTANCE = 0.00000E+00 INCHES
INITIAL CRACK LENGTH = 0.60000E+00INCHES
SPECIMEN THICKNESS = 0.25000E+00 INCHES

MATERIAL PROPERTIES

YIELD STRENGTH = 0.18205E+03 KSI
FRACTURE TOUGHNESS = 0.11630E+03 KSI-(IN)1/2
C-COEFFICIENT IN WALKER EQN = 0.27320E-10
M-EXPONENT IN WALKER EQN = 0.42000E+00
N-EXPONENT IN WALKER EQN = 0.32423E+01

LOAD PARAMETERS

MAX NO. OF REPEATED SEQUENCES=100000

R	# OF CYCLES	MIN LOAD (KSI)	MAX LOAD (KSI)
0.0000000E+00	3	0.0000000E+00	0.3000000E+01
0.0000000E+00	6	0.0000000E+00	0.1800000E+01
0.0000000E+00	12	0.0000000E+00	0.1350000E+01
0.0000000E+00	24	0.0000000E+00	0.1000000E+01

USES WALKER EQUATION AND DOES NOT ACCOUNT FOR INTERACTION EFFECTS

CRITICAL CRACK LENGTH FOR TOTAL YIELDING = 1.68295

REP#	CYCLE#	CI	A	DELTA K	DA/DN
1	1	0.1000000E+01	0.6000031E+00	0.3638020E+02	0.3142483E-05
4677	210423	0.1000000E+01	0.7000034E+00	0.4105995E+02	0.4652296E-05
7923	356491	0.1000000E+01	0.8000042E+00	0.4626865E+02	0.6852344E-05
10094	454221	0.1000000E+01	0.9000001E+00	0.1741194E+02	0.2881898E-06
11536	519078	0.1000000E+01	0.1000008E+01	0.5924631E+02	0.1527494E-04
12478	561507	0.1000000E+01	0.1099999E+01	0.2255898E+02	0.6673402E-06
13080	588557	0.1000000E+01	0.1200013E+01	0.7803627E+02	0.3731415E-04
13451	605256	0.1000000E+01	0.1300009E+01	0.5463676E+02	0.1174701E-04
13671	615157	0.1000000E+01	0.1400005E+01	0.6469234E+02	0.2031459E-04

FAILURE OCCURRED ON CYCLE NUMBER 617941 BLOCK NUMBER 13733
DUE TO BRITTLE FRACTURE.
KMAX = 0.1163692E+03 CRACK LENGTH = 0.1442090E+01

```
C*************************************************************************
C                          ------DATRED2------                            *
C     THIS PROGRAM REDUCES CRACK LENGTH-CYCLE NUMBER DATA TO DETERMINE    *
C     THE STRESS INTENSITY FACTOR RANGE AND THE CRACK GROWTH RATE.        *
C     THIS PROGRAM IS AN ADAPTATION OF ONE WRITTEN BY FONG AND DOWLING    *
C     THAT USES THE INCREMENTAL POLYNOMIAL METHOD OF REDUCTION.           *
C*************************************************************************
C                 ---------INPUT DATA INFORMATION---------                *
C     THE PROGRAM WILL READ TEST DATA SETS UNTIL IT RUNS OUT OF DATA TO*
C     READ.  THE FIRST CARD OF EACH DATA SET MUST HAVE THE FOLLOWING      *
C     FORMAT:  COLUMNS 1-30   ID    COLUMNS 31-36   N (RIGHT JUSTIFIED)*
C    *CARD 1:  FORMAT(A30,I6)                                             *
C     ID  =  SPECIMEN IDENTIFICATION VARIABLE (A30 FORMAT)                *
C     N   =  THE NUMBER OF TEST DATA POINTS (I6 FORMAT)                   *
C    *CARD 2:  FREE FORMAT                                                *
C     IST =  SPECIMEN GEOMETRY TYPE                                       *
C         IST = 1........COMPACT SPECIMEN WITH H/W=.486                   *
C         IST = 2........COMPACT SPECIMEN WITH H/W=.6                     *
C         IST = 3........CENTER CRACK SPECIMEN                            *
C         IST = 4........ARC-SHAPED SPECIMEN                              *
C    *CARD 3:  FREE FORMAT                                                *
C     PMIN=  MINIMUM LOAD                                                 *
C     DELP=  DIFFERENCE BETWEEN MINIMUM AND MAXIMUM LOAD                  *
C     F   =  TEST CYLE FREQUENCY                                          *
C     B   =  SPECIMEN THICKNESS                                           *
C     W   =  SPECIMEN WIDTH                                               *
C     A0  =  INITIAL CRACK LENGTH                                         *
C    *CARD 4:  FREE FORMAT(READ ONLY IF IST=4)                            *
C     X1  =  LOAD-TO-CRACK DISTANCE FOR ARC-SHAPED SPECIMEN               *
C     R1  =  INNER RADIUS FOR ARC-SHAPED SPECIMEN                         *
C     R2  =  OUTER RADIUS FOR ARD-SHAPED SPECIMEN                         *
C    *CARD 5:  FREE FORMAT(USE AS MANY CARDS AS SETS OF DATA POINTS)      *
C     A(I,2) =  CRACK LENGTH                                              *
C     A(I,1) =  CYCLE NUMBER                                              *
C*************************************************************************
      CHARACTER ID*30
      DIMENSION A(100,4),C(7),X(100),Y(100)
  998 READ(5,100,END=999)ID,N
      READ(5,*)IST
      READ(5,*)PMIN,DELP,F,B,W,A0
      IF(IST.EQ.4)READ(5,*)X1,R1,R2
      READ(5,*)(A(I,2),A(I,1),I=1,N)
      NN=N-3
      DO 1 I=1,N
      A(I,2)=A(I,2)+A0
    1 CONTINUE
      DO 2 I=4,NN
      C1=(A(I-3,1)+A(I+3,1))/2.
      C2=(A(I+3,1)-A(I-3,1))/2.
      DO 3 J=1,7
      C(J)=(A(I-4+J,1)-C1)/C2
    3 CONTINUE
```

```
      SX=0.
      SX2=0.
      SX3=0.
      SX4=0.
      SXY=0.
      SX2Y=0.
      SY=0.
      DO4 J=1,7
      SX=SX+C(J)
      SX2=SX2+C(J)**2
      SX3=SX3+C(J)**3
      SX4=SX4+C(J)**4
      SXY=SXY+C(J)*A(I-4+J,2)
      SX2Y=SX2Y+C(J)**2*A(I-4+J,2)
      SY=SY+A(I-4+J,2)
    4 CONTINUE
      DEN=7.*(SX2*SX4-SX3**2)-SX*(SX*SX4-SX2*SX3)+SX2*(SX*SX3-SX2**2)
      B0=(SY*(SX2*SX4-SX3**2)-SX*(SXY*SX4-SX2Y*SX3)+SX2*(SXY*SX3-SX2
     1*SX2Y))/DEN
      B1=(7.*(SXY*SX4-SX3*SX2Y)-SY*(SX*SX4-SX3*SX2)+SX2*(SX*SX2Y-SX2*SXY
     1))/DEN
      B2=(7.*(SX2*SX2Y-SX3*SXY)-SX*(SX*SX2Y-SX2*SXY)+SY*(SX*SX3-SX2**2
     1))/DEN
      A(I,3)=B0+B1*C(4)+B2*C(4)**2
      Y(I)=B1/C2+2.*B2*(A(I,1)-C1)/C2**2
      AW=A(I,3)/W
      XX=(2.+AW)/(1.-AW)**1.5
      GO TO (10,20,30,40),IST
C*****
C     COMPACT SPECIMEN  H/W=.486
C*****
   10 FAW=(.8072+8.858*AW-30.23*AW**2+41.088*AW**3-24.15*AW**4+4.951*
     1AW**5)*XX
      X(I)=DELP/SQRT(W)/B*FAW
      GO TO 2
C*****
C     COMPACT SPECIMEN  H/W=.6
C*****
   20 FAW=(.886+4.64*AW-13.32*AW**2+14.72*AW**3-5.6*AW**4)*XX
      X(I)=DELP/B/SQRT(W)*FAW
      GO TO 2
C*****
C     CENTER-CRACK SPECIMEN
C*****
   30 PI=ARCOS(-1.)
      FAW=SQRT(1./COS(PI*AW/2.))*(1.-.025*AW**2+.06*AW**4)
      X(I)=DELP*SQRT(PI*A(I,3))/B/W*FAW
      GO TO 2
C*****
C     ARC-SHAPED SPECIMEN
C*****
   40 AW=A(I,3)/(R2-R1)
```

```
      FAW=SQRT(AW)/(1.-AW)**1.5*(3.74-6.3*AW+6.32*AW**2-2.43*AW**3)
      X(I)=DELP/B/SQRT(W)*(3.*X1/W+1.9+1.1*AW)*(1.+.25*(1.-AW)**2*(1-
     1R1/R2))*FAW
    2 CONTINUE
      R=PMIN/(PMIN+DELP)
      WRITE(6,115)
      WRITE(6,120)
      WRITE(6,103)ID
      IF(IST.EQ.1)WRITE(6,104)
      IF(IST.EQ.2)WRITE(6,105)
      IF(IST.EQ.3)WRITE(6,121)
      IF(IST.EQ.4)WRITE(6,122)X1,R1,R2
      WRITE(6,109)DELP,PMIN,R
      WRITE(6,110)B,W,A0
      WRITE(6,111)F
      WRITE(6,114)
      DO 11 I=1,3
      WRITE(6,112)(A(I,J),J=1,2)
   11 CONTINUE
      DO 12 I=4,NN
      WRITE(6,113 )(A(I,J),J=1,3),X(I),Y(I)
   12 CONTINUE
      NN=NN+1
      DO 13 I=NN,N
      WRITE(6,112)(A(I,J),J=1,2)
   13 CONTINUE
      GO TO 998
  999 CONTINUE
  100 FORMAT(A30,I6)
  103 FORMAT(/21X,A30)
  104 FORMAT(/20X,'COMPACT SPECIMEN H/W=0.486')
  105 FORMAT(/20X,'COMPACT SPECIMEN H/W=0.6')
  109 FORMAT(/' DELTA P=',F9.4,' KIPS   PMIN=',F9.4,' KIPS  R=',F7.4)
  110 FORMAT(' B=',F8.4,' INCHES  W=',F8.4,' INCHES  A0=',F8.4,' INCHES'
     1)
  111 FORMAT(' TESTING FREQUENCY=',F8.4,' HERTZ')
  112 FORMAT(F9.0,F14.4)
  113 FORMAT(F9.0,F14.4,F11.4,F12.2,1PE15.3)
  114 FORMAT(/'     TOTAL',11X,'CRACK LENGTH',8X,'STRESS',6X,'GROWTH',/
     1'    CYCLES',7X,'OBSERVED  CALCULATED  INTENSITY',5X,'RATE')
  115 FORMAT(1H1)
  120 FORMAT(' ',9X,'CRACK GROWTH RATE AND STRESS INTENSITY DATA REDUCTI
     1ON',/20X,'INCREMENTAL POLYNOMIAL FOR DA/DN')
  121 FORMAT(/20X,'CENTER-CRACK SPECIMEN')
  122 FORMAT(/20X,'ARC-SHAPED SPECIMEN'/20X,'LOAD-TO-CRACK DISTANCE =',
     1F6.4,' INCHES'/20X,'R1 =',F6.4,'INCHES  R2 = ',F6.4,'INCHES')
      END
```

```
C***********************************************************************
C                          ------DATFIT-----                           *
C     THIS PROGRAM CALCULATES A LINEAR LEAST SQUARES FIT ON CRACK      *
C     GROWTH DATA AND GIVES A MEASURE OF FIT.  IT WILL ALSO GENERATE   *
C     DIFFERENT WALKER C-CONSTANTS BY VARYING THE WALKER M-EXPONENT.   *
C     THE PROGRAM WILL PRINT THE BEST FIT OF THE CONSTANTS BASED ON    *
C     THE CORRELATION COEFFICIENT.                                     *
C***********************************************************************
      COMMON/ONE/DK(20,50),DN(20,50),L,N(50),R(20)/TWO/X(500),Y(500),JJ
C*****
C     READ IN THE INPUT DATA POINTS
C*****
           CALL INPUT
           BEST=0.
C*****
C     BEGIN LOOP ON M-EXPONENT IN WALKER EQUATION.  ALL CALCULATIONS
C     WILL BE DONE AT EACH VALUE OF THE M-EXPONENT AND THE VALUE THAT
C     YIELDS THE BEST CORRELATION WILL BE CHOSEN.
C*****
           DO 100 II=1,51
           WALKM=.2+II*0.01
           CALL EQUIV(WALKM)
           CALL LESTSQ(C,WALKN,VAR,COREL)
           WALKC=1./(10.**ABS(C))
           IF(COREL.GT.BEST)THEN
           BEST=COREL
           BV=VAR
           WM=WALKM
           WN=WALKN
           WC=WALKC
           END IF
  100 CONTINUE
           WRITE(6,1002)
           WRITE(6,1000)JJ,BV,BEST
           WRITE(6,1001)WM,WN,WC
C
 1000 FORMAT(1H ,'NUMBER OF DATA POINTS = ',I5/
     1/' DATA VARIANCE = ',E15.7/,1X,'DATA CORRELATION = ',E15.7//T16,
     2'WALKM',T31,'WALKN',T46,'WALKC',/'+',T11,45('_')/)
 1001 FORMAT(T11,3E15.7////)
 1002 FORMAT(////'THE BEST FIT IS:'//)
      END
C***********************************************************************
      SUBROUTINE LESTSQ(A,B,VAR,RHO)
C*****
C     THIS SUBROUTINE CALCULATES A LINEAR LEAST SQUARE DATA FIT AND
C     GENERATES THE SLOPE AND Y=INTERCEPT,A AND B, RESPECTIVELY.
C     IT ALSO CALCULATES VARIANCE IN Y AND CORRELATION COEFFICIENT,RHO.
C*****
      COMMON/TWO/X(500),Y(500),JJ
      XSUM=0.0
      YSUM=0.0
```

```
      XSUM2=0.0
      XYSUM=0.0
      SUM=0.0
      YSUM2=0.0
C*****
C     BEGIN LOOP ON DATA POINTS
C*****
           DO 10 I=1,JJ
           XSUM=X(I)+XSUM
           YSUM=Y(I)+YSUM
           XYSUM=X(I)*Y(I)+XYSUM
           XSUM2=X(I)*X(I)+XSUM2
   10      YSUM2=Y(I)*Y(I)+YSUM2
      DENOM=JJ*XSUM2-XSUM**2
      A=(XSUM2*YSUM-XSUM*XYSUM)/DENOM
      B=(JJ*XYSUM-XSUM*YSUM)/DENOM
C*****
C     CALCULATE THE CORRELATION COEFFICIENT AND THE VARIANCE
C*****
          DO 20 I=1,JJ
   20     SUM=(Y(I)-B*X(I)-1)**2
      VAR=SUM/(JJ-2)
      RHO=(JJ*XYSUM-XSUM*YSUM)/SQRT(DENOM*(JJ*YSUM2-YSUM**2))
      RETURN
      END
C************************************************************************
      SUBROUTINE INPUT
C*****
C     THIS SUBROUTINE READS DELTA K VS DA/DN DATA FROM A FILE.
C     ALL INPUT IS FREE-FORMATTED.
C*****
      COMMON/ONE/DK(20,50),DN(20,50),L,N(50),R(20)/TWO/X(500),Y(500),JJ
C*****
C     THE VARIABLE L REPRESENTS THE NUMBER OF TEST DATA SETS BEING READ
C     AND N(I), R(I) ARE THE NUMBER OF DATA POINTS IN A TEST DATA SET
C     AND THE LOAD RATIO OF THE TEST.
C*****
      READ(5,*)L
      DO 30 I=1,L
      READ(5,*)N(I),R(I)
               DO 30 J=1,N(I)
   30         READ(5,*)DK(I,J),DN(I,J)
      RETURN
      END
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      SUBROUTINE EQUIV(WALKM)
C*****
C     THIS SUBROUTINE MANIPULATES THE INPUT DATA POINTS.  THE INPUT
C     DELTA K VALUES ARE CONVERTED TO AN EQUIVALENT DELTA K BASED ON THE
C     WALKER EQUATION AND COMPRESSION VALUES ARE IGNORED BY SETTING THE
C     EQUIVALENT DELTA K FOR COMPRESSIVE LOADS EQUAL TO THE MAX K FOR
```

```
C     THE CYCLE.  THE DATA POINTS ARE CONVERTED TO BASE 10 LOGARITHMS.
C*****
      DIMENSION DKEQ(10,50)
      COMMON/ONE/DK(20,50),DN(20,50),L,N(50),R(20)/TWO/X(500),Y(500),JJ
      JJ=0
      DO 40 I=1,L
      XM=WALKM
           DO 40 J=1,N(I)
           IF(R(I).LT.0.)XM=0.
           DKEQ(I,J)=DK(I,J)/(1.-R(I))**(1.-XM)
           JJ=JJ+1
C          WRITE(6,*) DKEQ(I,J),DN(I,J)
           X(JJ)=ALOG10(DKEQ(I,J))
   40      Y(JJ)=ALOG10(DN(I,J))
      RETURN
      END
```

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